Modelling, Simulation and Analysis of NPDA for Sub-retinal implant using Nano Materials

M. VijaiMeyyappan¹ and R. Joseph Daniel ²
¹ Assistant Professor, M.I.E.T. Engineering College, Dept. of Electronics and Communication Engg., Gundur, Trichy, 620 007
² Professor, NPMaSS MEMS Design Centre, Dept. of Electronics and Instrumentation Engg., FEAT, Annamalai University, 608 002

corresponding author’s e-mail address: vijaimeyyappan@gmail.com

Abstract. There are two primary illnesses that afflict the elderly worldwide those are Retinitis Pigmentosa (RP) and Age-related Macula Degeneration (AMD). Presently there has been a large research focus to develop treatment methods that would cure AMD induced vision disability and RP diseases. Silicon Micro Photo Diode Array, ARGUS II, and ALPHA IMS are a few of the latest therapeutic approaches suggested for curing these diseases (MPDA). These systems have led to many undesirable side effects in patients. The objective of this research work is to create an affordable device that improves the vision recovery. Photovoltaic cells composed of nanomaterials such as carbon nanotubes and graphene are known as Nano Photo Diode Arrays (NPDA). Under incident light, they may generate stimulating electrical pulses to restore vision, photoreceptor cells are stimulated in the retina. The authors of this study sought to optimise the several geometries of Graphene/SWCNT-C60/Al bilayer hetero junction photodiodes that would constitute the NPDA for subretinal implantation.

1. Introduction

The eye is a vital organ that provides us with the ability to see and understand much about our surrounding environment. The neural signals are decoded by the visual cortex into coherent image clarification. Signal processing and convergence is carried out by various neural cell layers in the retina. Rods are highly light-sensitive and responsible for peripheral vision. Color vision and sharp images are regulated by cones. Horizontal cells aid in the integration and regulation of multiple photoreceptor cell information. The electrical signal is converted into electrical pulse trains by the bipolar cells, which keep the spatiotemporal details. Via the optic nerve, electrical pulses are sent to the brain's visual cortex. Amacrine cells manipulate retinal signal processing in response to visual stimuli. Ganglion cells collect visual information from bipolar cells and amacrine cells in their dendrites, which they then transmit to the brain via axon [1]. Figure 1 (a) shows how light enters the retina neural layer before the photoreceptors.
Eye diseases including AMD and RP, which cause visual impairments by completely degenerating the retina, are affecting an increasing number of individuals worldwide. AMD is the most prevalent source of blindness for the persons above the age of 55 [2]. It harms the macula, a tiny patch near the centre of the retina and the portion of the eye required for clear, central vision, which allows us to perceive objects front of you. A blurry region around the middle of vision is a frequent AMD symptom. Millions of light sensing cells make up the macula area, as shown in Figure 1(b), which provides bright, central vision. It's around 5.5 mm in diameter (0.22 in). It is situated in the rear of the eye the most sensitive part in retina.

Figure 1(a). The light reaches the retina neural layer before the photoreceptors

Figure 1(b). Macula region in an eye
If macula is damaged, the centre of angle of vision may look hazy, distorted, or dark. This disease will lead to progressive loss of central vision. Retinitis Pigmentosa is a common and debilitating cause of vision loss in both the central and peripheral vision. RP is an inherited disorder [3]. Outer retinal degeneration causes RP. This damages the other half of the inner anatomical retina, which is made up mainly of photoreceptors’ outer and inner parts, as well as their cell bodies. RP is most often diagnosed in infants, teenagers, and young adults, with the disorder progressing over their lives. In the early stages of RP, people are likely to experience night blindness, and later on, their vision and field of view can gradually deteriorate. Others become fully blind as a result of RP, which may occur as early as infancy. The progression of RP can vary from case to case. The retinal cells gradually lose their ability to function and ultimately die. The peripheral rod cells are usually the first to be affected by RP, followed by the central cone cells [4]. In short, both RP and AMD cause photoreceptor cells to degenerate, rendering the visual system insensitive to light.

For those suffering from AMD or RP, there is no effective treatment available. They urgently need an alternate method for allowing the world's sights to reach the brain and be perceived. Professor Wilfried Mokwa of RWTH Aachen University claims that 30 percent of RP patients' retinal ganglion cells are still active after years of blindness [5]. As a result, the following two remedial techniques have been investigated all over the world.

i. Bypass the degenerated photoreceptors appears to be a viable option. As a result, electrical impulses are elicited in retinal ganglion cells, resulting in a visual sense. This concept is said to be Epi-retinal implant.

ii. A sub-retinal implant is the second choice. A chip replaces the deteriorated photoreceptors with a MPDA in this operation. A picture is recorded onto the MPDA using the normal optics of the eye.

Epi-retinal implants, on the other hand, with fewer electrodes, employ electrical stimulation to produce the sense of visual perception, and do all image processing outside. [5]. Figure 2 depicts a schematic diagram of Epi-retinal and Sub-retinal implants. Because of the numerous benefits, the sub-retinal implant is the most widely researched alternative. The sub-retinal implant works by using 1,500 electrodes to replace the role of degenerated photoreceptors and processing images internally. Only a few photodiode-based prostheses that have been developed and implemented successfully.
Regardless of the reality Argus® II device efficiently generates phosphenes in reaction to visual inputs, in a handful of seconds, the apparent picture might fade away, causing image persistence problems. The protocol for further implantation is much too complicated. They also need external devices.

In the 1980s, Chow and colleagues created the device called Artificial Silicone Retina (ASR) for subretinal[7] was the first application of this technique. However, after 9 months, there was evidence of corrosion [8]. Finally, because the MPDA was developed on stiff silicon substrates, implant of these devices proved challenging. As a result, developing a foldable flexible substrate sub-retinal implant device is critical.

In this study, we investigate the feasibility of successfully implementing Nano Photo Diode Array (NPDA) using nano organic materials such as graphene, Semiconducting (S-SWCNT), conducting polymers and fullerene C$_{60}$buck ball for sub-retinal implant. This proposed NPDA will stimulate the degenerated retina and restore the vision efficiently and it doesn’t require any external equipment and power supply. Further the biocompatibility of the materials used in this NPDA is much superior. The biological responses that occur as a result of the surgery, foreign objects, and the effects of electrical stimulation all fall under the category of biocompatibility. Finally, relative to current computers, it is more adaptable.

2. Proposed Method

The authors intend to convert light intensity to stimulus current using a passive photovoltaic nano photo diode in this analysis. The primary goal of this project is to investigate the dependence of the photodiode performance on the layer thickness and material properties as well as to modify the design in order to fulfil the performance criteria for human subretinal implants. This section discusses the nano photodiode structure, operation and evaluation of photodiode performance using specific simulation tools.

2.1 Nano Photo Diode Array structure

NPDA structure includes polymer, carbon nanotubes, graphene, and aluminum material. This NPDA generates power under incident light to stimulate the retina for regaining lost vision function.

Figure 3 depicts the proposed Nano Photo Diode cell structure. The cathode is aluminium alloy, the electron donor is SWCNT, C$_{60}$bucky ball fullerenes is the electron acceptor, and the anode is graphene. The performance and transparency of the NPDA are improved by processing these materials over a flexible substrate [10, 11].

In this structure as diagrammed in Figure 3, Between two electrodes, a donor and an acceptor with differing band gaps are utilized in this work are placed together having different work functions, graphene (5.3eV - Anode) and aluminium (4.2eV - Cathode).

![Figure 3. Structure of Single NPD cell](image-url)
These two layers, graphene and aluminum electrodes, are associated with the formation of excitons. The work function of the electrode and semiconducting materials employed in this study are shown in Figure 4.

The transparent electrode is made of graphene. Graphene is a promising substrate in solar cell applications because of its strong and unique properties, huge area, water vapour, and lack of reactivity to oxygen. It is a suitable substitute for Indium Tin Oxide (ITO), which is costly and brittle in nature. ITO is also incompatible with foldable organic solar cells. Graphene is a feasible alternative for applications needing minimal cost and adaptability [12].

S-SWCNTs have a unique characteristics and combination of organic semiconductor. These characteristics make SWCNT the best candidate for use as a donor material in this study [13].

The electron acceptor C60 fullerene were chosen because it has better compatibility and allows for higher-quality blends with a donor material. Wet chemistry is also used to process it. Charge separation is possible when the donor's Low Unoccupied Molecular Orbit (LUMO) is higher than the acceptor's LUMO and the donor's High Occupied Molecular Orbit (HOMO) is greater than the acceptor's HOMO. It's a prerequisite, but not adequate. As can be seen in Figure 4, this condition is fulfilled by the materials chosen. For charge separation to occur, the combination of these differences in electron affinity and ionisation potential outcomes must be able to resolve the exciton binding energy [14].

Cathode metal should have a lower work function than anode metal. The work function of aluminium (4.2eV) is lower than that of graphene (5.3eV), so it meets the requirements.

The electrode materials and active layers are deposited one after the other in this method for forming a bond between two distinct materials. As a result, it is referred to as a bi-layer junction solar cell. Figure 5 depicts the proposed NPDA structure, it has a 3mm×3mm size.

2.2 Nano Photo Diode operation

2.2.1 Photovoltaic impact and photovoltaic voltage

The photovoltaic impact is what allows photovoltaic (or solar) cells to convert light into electricity. Light, which is pure energy, enters a PV cell and gives certain electrons (negatively charged atomic particles) enough energy to make them free [15].

Depending on carbon atoms that have been sp2-hybridized, Organic solar cell materials are generally composed of alternating single bonds and double bonds (conjugated structure). The electrons...
will reside in two energy states due to the $\pi-\pi^*$ interactions amongst the bonding and anti-bonding $pz$ orbitals. The molecular structure of the organic semiconductor can be changed to adjust their location and separation. Figure 4 depicts the energy band diagram for various materials. The donor's relative HOMO (ionisation potential) energy level and the acceptor's LUMO (electron affinity) determine the photovoltage ($V_{oc}$).

$$V_{oc} = [E_{\text{Donor HOMO}} - E_{\text{Accepto LUMO}}]$$

(1)

### 2.2.2 Device Physics of PHJ photo voltaic

A PHJ photovoltaic cell is made up of semiconductors. Planar heterojunction is another name for this structure. The photo-generated singlet excitons might permeate through the donor to the planar contact with the second material, which is typically very electronegative. That the electron will go to a lower energy state within the acceptor, the energy required to detach the singlet exciton is provided by the acceptor material. As a result of the charge transmission, the exciton is separated, and the electron transfers to the acceptor substrate while the hole remains on the donor. The $C_{60}$ fullerence is well-known electron acceptor material.

Light absorption, excitons diffusion to an active interface, charge isolation, charge transfer, and charge collection are all phases in the functioning of an organic photovoltaic cell. Figure 6(a) – 6(d) depicts the stages involved in OPV energy conversion.

The first step is light absorption, which leads to the forming of exciton. When light strikes photosensitive semiconductor organic materials, electrons in the HOMO state are stimulated to the LUMO state, as a result, excitons arise in the donor material. The light absorption that leads to exciton formation is depicted in Figure 6(a). Excitons, or closely bonded electron hole pairs, develop and diffuse within an organic semiconductor that is unaffected by an applied electric field. The exciton diffusion is depicted in Figure 6(b). The excitons produced as a result of light absorption can contribute to the the development of free charge carriers in order to make an effective organic solar cell.

![Figure 6. (a-d): Stages involved in OPV energy conversion](image-url)
The exponential lifetime of an exciton (τ). Diffusion transports excitons, and distance (L) calculates an exciton as follows:

\[ L = \sqrt{\tau \times D} \]  \hspace{1cm} (2)

D denotes the excitons' diffusion coefficient. The resulting holes and electrons must migrate through the conductivity organic materials used to connect the device's exterior contacts once an exciton is divided into free charge carriers. The charge transport and set are depicted in Figure 6(c-d). The relationship between the velocity (\(V_{di}\)) The charge carriers that are acquired as a result of an electric field's influence (\(\xi\)) is:

\[ V_{di} = \mu \cdot \xi \]  \hspace{1cm} (3)

in which \(\mu\) is the mobility. Charges must frequently surpass the things in order to permeate a poor work capacity electrode material (Ca or Al).

3. Simulation studies

Organic Photo Voltaic (OPV) tool was used to model and simulate the modern hybrid design nano photodiode cell utilizing Nano materials in order to optimize NPDA device.

3.1 Simulation Software tool OPV

This tool is a universal learning resource[16]. The present work uses Graphene/SWCNT/C_{60}/Al cell structure as diagrammed in Figure 3 for NPDA. This structure was created for simulation by defining various thickness as and other physical parameters. These Nano Photodiode cell models are subjected to simulations in order to determine their parameters, the parameters are obtained from I-V characteristics as illustrated in Figure 7. A bias voltage of 0.0V to 0.9V with a 0.05 phase increase is provided to the anode contact.

![Figure 7. Organic solar cell I-V characteristics in the IV Quadrant.](image)

\[ J_{\text{dark}}(V) = J_o (e^{qV/K_BT} - 1) \]  \hspace{1cm} (4)

The dark current density \(J_{\text{dark}}(V)\)is for an ideal organic solar cell, \(J_o\) denotes a constant, KB denotes Boltzmann's constant, and \(T\) denotes Kelvin temperature. The total number of short circuit photocurrents and dark currents can be used to approximate the cell's total current voltage response. Despite the fact that the reverse current flowing in an illuminated cell in response to voltage is not strictly equal to the current flowing in the dark, for certain photovoltaic materials, the approximation is rational. The sign standard for voltages and currents. The cell's net current density is:

\[ J(V) = J_{\text{aqe}}(V) - J_{sc} \]  \hspace{1cm} (5)
which can be written as

$$J(V) = J_o (e^{qV/kT} - 1) - J_{sc}$$

(6)

for an ideal diode.

Open circuit voltage ($V_{oc}$) is the potential difference reaches its highest value when the connections are disconnected. In order to create the optimal diode,

$$V_{oc} = \frac{KT}{q} \ln\left(\frac{J_{sc}}{J_o} + 1\right)$$

(7)

Equation (7) indicates a logarithmic rise in $V_{oc}$ with the intensity of light. Figure 7 indicates that the current-voltage product is negative and that when the voltage is between 0 and $V_{oc}$ the cell produces electricity. The illuminated device $V<0$ functions as a photodetector and consumes electricity to produce a light-dependent but partially independent photo current. The system absorbs power again at $V> V_{oc}$. This is the area where diodes are emitted from light.

Fill Factor is calculated by

$$FF = \frac{I_{max} * V_{max}}{I_{sc} * V_{oc}}$$

(8)

Where $I_{max}$ and $V_{max}$ are maximal power points of current and voltage. The overall power conversion efficiency $\eta$ is defined as

$$\eta = \frac{I_{max} * V_{max}}{P_{in}} = \frac{(FF * (I_{sc} * V_{oc})))}{P_{in}}$$

(9)

The short-circuit current density is calculated by

$$J_{sc} = \frac{qG(L_n + L_p)}{P_{in}}$$

(10)

Where generation rate is denoted by $G$, and electron lengths is denoted by $L_n$ and lengths of the hole diffusion is denoted by $L_p$ respectively.

### 3.2 Impact of Anode Layer thickness on performance

Graphene is used as an electrode in the nano photodiode. The impact of anode layer thickness on parameter diodes is defined in this section. The thickness of Graphene ranges from 25nm to 200nm though preserving donor is having constant thickness, receiver and aluminium layer thickness of about 50 nm. The anode layer thickness of 100 nm I-V curves is depicted in Figure 8. The thickness of donor, acceptor and cathode layers is 50 nm. The thick anode decreases the transmission of light and low sheet resistance.
3.3 Impact of anode layer thickness on Voc

The variation of \( V_{oc} \) in relation to the anode layer thickness is seen in figure 9. From this figure it is evident that \( V_{oc} \) is not influenced by the anode layer thickness. This suggests that the graphene layer thickness doesn’t play any role on the creation of excitons.

3.4 \( J_{sc} \) density is affected by the thickness of the anode layer

According to the simulation findings, the Figure 10 shows that the \( J_{sc} \) is improved due to high lights transmittance and low sheet resistance, if anode thickness rises between 25 and 100 nm. Graphene thickness increases leads to a falling current density owing to poor light transmission due to the thickness from 100 nm to 200 nm of the anode.
3.5 Impact of Graphene layer thickness on Efficiency

The ratio of output power and input power is defined as efficiency. Even with strong light transmission, when anode thickness grows, efficiency improves from 15 nm to 110 nm. Low sheet resistance results in increase in anode-thickness. As the thickness of the graphene increases from 110 nm to 210 nm, the efficacy of anode thickness reduces owing to low light transmission. When all above-mentioned parameters are decreased, as seen in Figure 11, device efficiency also decreases.

![Anode Layer Thickness vs. Efficiency Plot](image1)

**Figure 11.** Anode Layer Thickness vs. Efficiency Plot.

![Graphene Layer thickness Vs Fill Factor Plot](image2)

**Figure 12.** Graphene Layer thickness Vs Fill Factor Plot.

3.6 The thickness of the Graphene layer impact on the Fill Factor

Figure 12 shows that the FF is inverted in terms of $J_{sc}$ and $\eta$. Diminishes the FF as $J_{sc}$ and $\eta$ increases.

3.7 Active Layer thickness Impact on performance

Active layer thickness effects accomplished utilizing modelling and are compared to active layer thickness, on different parameters. In this analysis, the donor and acceptor thickness varies between 20 nm and 200 nm. The thickness of the anode and the cathode is stable. Figure 13 depicts the I-V curve with an Donor-acceptor layer thickness of 60 nm.

![PV device I-V characteristics donor-acceptor layer thickness](image3)

**Figure 13.** PV device I-V characteristics donor-acceptor layer thickness.

3.8 The impact of Donor-acceptor layer thickness on $V_{oc}$

Figure 14 shows that the $V_{oc}$ value declines insignificantly. The operating circuit volt is solely determined by the difference in the equation (1) between HOMO donor and LUMO acceptor.
3.9 $J_{sc}$ effect on active layer thickness

Figure 16 depicts fluctuation of efficiency with donor/acceptor layer thickness. The device's efficiency declines when the parameters $V_{oc}$, $J_{sc}$, and $FF$ have been reduced. According to this study, efficiency of more than 1% may be impossible.

![Figure 14. Donor/acceptor Layer Thickness vs. $V_{oc}$ Plot.](image)

3.10 Impact of active layer thickness on Efficiency

Figure 16 depicts the Donor/Acceptor layer thickness impact on efficiency. The efficiency of the device decreases as the parameters $V_{oc}$, $J_{sc}$, $FF$ are decreased. This analysis shows that more than % productivity might not be feasible.

3.11 Fill Factor Effect of Active Layer Thickness

The rise of Donor-Acceptor layer thickness over electrode thickness would marginally reduce the fill factor as seen in Figure 17. It indicates that under I-V characteristic curves the maximal power obtained decreases by an increasing thickness. As a result, thickness of the Donor-Acceptor layer increases it decreases.
3.12 Thickness of the cathode layer has an effect on performance

Simulation results clearly show that the performances of both the variation on cathode layer thickness and anode layer thickness resulting in similar output.

The increase in cathode thickness will increase the efficiency. The bottom of the solar cell is the Cathode. Therefore, in optical absorption, it has no function. The collection of charges is the responsibility of Cathode.

3.13 Design Optimization

The analysis above and the results of the different NPDA parameters show that the following are the ideal layer thicknesses to increase the efficiency. Now it is essential to design the geometries of layers for the PHJ devices to be fabricated. The simulation results form the basis for the design of optimum geometries for the the finest performance. It is worth noting that maximizing the efficiency is the key to achieve the best possible performance. This study present the simulation studies carried out for optimizing the Nano Photodiode (NPD) geometries using simulation tool. Several PHJ devices were simulated and compare their performance parameters. Based on the results the design guidelines for achieving optimum photocurrent density and photovoltage for subretinal stimulation applications were generated and optimum design was arrived at.

4. Conclusion

RP and AMD are the two main conditions leading to human vision loss. For retina implants in the past, MPDA was considered. The results discussed in the previous sections show that the transmittance of light reduces as the anode layer thickness is increased beyond 100 nm. It is also demonstrated that it is not able to stop the BHJ devices in producing higher efficiency even if the thickness of anode layer is more than 100 nm. The results further indicate that the efficiency of PHJ devices will be more as its thickness increases. Cathode layer thickness plays no role in efficiency improvement. Therefore, it is kept 50 nm layer thicknesses. The result of the single PHJ NPD optimum layer thickness presented in Table 1 indicates that it should be sufficient to produce the necessary photo voltage and photocurrent for stimulating a single nerve cell. More corrosive, though, leading to damage to the implant system itself [2]. This is also bio incompatible. A potential solution is NPDA nano-materials such as CNT and graphene made on bio-compatible versatile substrates. This NPDA, which produces power under light incident to stimulate retina, does not require an external power source to recover impaired vision function. This current structure of NPDA is more robust and can increase the level of vision dramatically. This work aims to optimize the diode configuration and geometry to maximize the efficiency of the photodiode array.

| Layer   | Material | Layer thickness |
|---------|----------|-----------------|
| Anode   | Graphene | 100 nm          |
| Donor   | SWCNT    | 50 nm           |
| Acceptor| C60      | 50 nm           |
| Cathode | Aluminum | 50 m            |

Table 1: Optimum layer thicknesses.
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