Development of ZnO-PVA based Polymer Composite Films by Solution Casting Approach for Performance Maximization of Organic Solar Cells

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Abstract

Organic Solar Cells (OSCs) are becoming incredibly popular in photovoltaics because to their solution tunability, flexibility, low temperature development, environmental friendliness and ease of integration. Despite these benefits, the energy conversion efficiency of OSCs is lowest than that of other cells based on solar energy. As a result, the emphasis will unavoidably be on boosting the efficiency of OSCs. With this concept, we created and incorporated a ZnO-PVA nanocomposite (NCs) film to see whether we could improve its efficiency. ZnO nanoparticles with several different concentrations in a PVA matrix were used to prepare the NCs films following the Solution Casting Approach. Each sample of all NCs films was analyzed using OSCs. The efficiency of OSCs differs significantly before and after application of prepared NCs coating. When applied on OSCs with structure [Carbon Fiber)/(CuO/Epoxy Resin)/(ZnO/Epoxy Resin)/Carbon Fiber], the film with an ideal Wt.% of ZnO; 14.50 percent and PVA; 85.50 percent, exhibits a substantial increase in performance efficiency.

Introduction

Nanotechnology offers enormous promise for harvesting solar energy effectively utilizing photovoltaic (PV) cells. Furthermore, nanotechnology has grown as a multidisciplinary discipline, with rising importance in several fields of engineering. When inorganic cells are doped with silicon and organic cells with polymer, nano particles (NPs) operate as semi-conductive components in PV cells (Khan, Rahman et al. 2021). Polymeric materials (PMs) are utilized to replace traditional materials because they are light in weight, inexpensive, and have superior physio-chemical qualities (Mohammed, Khafagy et al. 2021). Significant attempts have been made to build diverse NCs in order to grasp their underlying principles in numerous domains of engineering (Ferrone, Araneo et al. 2019).

Characteristics (such as electrical, optical, structural, and mechanical) of PMs may be effectively adjusted by adding tiny quantities of nano fillers into polymer matrices (Manikandan, Imran et al. 2019). Because of its diverse features, ZnO NPs are employed in a variety of applications, including UV absorption and photoelectronic devices. Doping of ZnO NPs into a basic polymer matrix has shown to be quite useful in measuring the physical characteristics of PCMs (Ramadan 2018). These NPs appear to create a compound with the polymer chain, improving the physical characteristics of the Polymeric Composite Materials (PCMs).

In recent years, PVA (polyvinyl alcohol) has been employed as a simple polymer with specialized features such as strong stability, bio-degradability, environmental stability, optical and electrical properties. The presence of crystalline and amorphous zones, which causes concentric amorphous-crystal effects to boost physical properties, is a crucial property of PVA's semi-crystalline nature (Lou, Osemwegie et al. 2020).

Organic materials, especially semiconducting polymeric materials, have been used as light absorbers in the third generation of OSCs, which have been used to create solution-treated solar cells (Leong, Wang et al. 2022). Third-generation OSCs primarily need the usage of PCMs, which provide cheaper production costs as well as increased performance. NCs have been increasingly used in assembly of 3rd generation OSCs, i.e., thin film OSCs, to increase the harvesting of solar energy (Srivastava 2017). The environmental stability, conductivity, and optical absorption of the NCs are the most important criteria for determining the material's feasibility for solar energy utilization.

PCMs are gaining popularity in optoelectronics. ZnO NCs have piqued the interest of many researchers due to their wide range of applications (Sangwan, Malik et al. 2021). The addition of ZnO NPs to PVA structures can change its electrical, optical, and mechanical attributes of polymers. A multitude of processes are used to create polymers based NCs (Khan, Zain et al. 2021). Each approach has its own distinct features. However, regardless of approach, the major emphasis of all PCMs is on final morphology (VG and Augustine M 2011), which is dependent on interactions between PCMs that enable excellent dispersion of NPs in polymer matrix (Wu, Zhang et al. 2021).

The Solution Casting Approach (SCA) is an ancient approach for development the PCMs films that was chosen because of its simple processes for the fabrication of ZnO embedded PVA NCs thin films with regular thickness. Because of its numerous optoelectronic applications, the physical characteristics of ZnO-PVA NCs are crucial (Srivastava 2016).

The optical and electrical attributes of PVA matrix were tailored by addition of ZnO nano fillers, and this idea was taken from a published research study (Khan, Zain et al. 2021). Although reports have shown that ZnO-PVA NCs film has the potential to be employed in optoelectronics, but research studies on application of ZnO-PVA NCs films in OSCs has not been published in details. As a result, some attempts have been engaged in current study to demonstrate the performance efficacy of ZnO embedded PVA NCs films for improvement. Carbon (CF), Epoxy Resin (ER), CuO Layer and ZnO Layer were used to make the OSCs. The impact of adding the self-developed ZnO-PVA NCs films on efficiency of an OSCs with internal structure [CF)/(ZnO/ER)/(CuO/ER)/CF] was investigated.

Materials & Methods

Preparation of ZnO /PVA NCs films

SCA was used to fabricate the NCs films of ZnO-PVA. To proceed, an aqueous solution of PVA was prepared by mixing PVA with water. To prepare a stock solution, PVA (4.0 ± 0.1 grams) was added in water (100 ± 0.5mL). To prepare the uniform PVA solution, magnetic stirrer with speed of 450 rpm for two hours at 75 ^{o}C was utilized. Then, quantities of ZnO were added to the aqueous solution of PVA. The solutions were then placed in ovens set at 45^{o}C-65^{o}C for 24–48 hours.

The film was then readily removed from ceramic dish which was obtained as a versatile film. Following the above method, the films of PVA/ZnO NCs with varying amounts of ZnO NPs were prepared (Table 1).

Table 1
Prepared NCs films

Hybrid Cell	NCs Film Codes	%wt of ZnO	%wt of PVA	Film Thickness
ZnO(1)-PVA(6)	NC-1	16.5	83.5	0.031 mm
ZnO(2)-PVA(6)	NC-2	27.5	72.5	0.041 mm
ZnO(3)-PVA(6)	NC-3	35.5	64.5	0.052 mm
ZnO(4)-PVA(6)	NC-4	43	57.0	0.069 mm
ZnO(6)-PVA(10)	NC-5	39	61.0	0.11 mm

To develop a better and more effective films, 5 different films of ZnO-PVA NCs with varying %weights of ZnO and PVA were prepared. The lab scale NCs thin films have been fabricated based on size of 132 × 62 (mm), depicted in Fig. 1. The thickness of NCs films differs in range of 0.024–0.12 (mm).

Energy Band Gap (EBG) Study of Prepared Films

The prepared ZnO-PVA NCs films were characterized using Varian Cary 100 UV-VIS Spectrophotometer by Agilent Technologies, California to study the EBG. The equipment in this experiment was calibrated first to achieve its standard state. The films were then kept in chamber parallel to ultra violet source, allowing light rays of certain wavelength to penetrate on the sample's substrate passing through the deposited layer. As a result, the EBG was computed, and the presence of ZnO NPs in the PVA matrix had a substantial impact on it.

Designing the OSCs

The OSCs were created as a separator/salt aqueous electrolyte employing conductive polymers of copper oxide (CuO) and prepared NCs film, CF, and dielectric. To convert and store solar energy, the fundamental design scheme of the OSCs is to optimize optical absorption and to minimise the loss during electron transit. The NCs film structure improves the efficiency of OSCs by increasing the generation effect of exciton within the quantum dots, producing a huge surface area, giving particular optic influences, as well as facilitating electron transit and gathering.

NCs films are fabricated in the form of nanowires, having less material flaws. As a result, single crystal layer permits for substantially increased movement and very efficient in transportation of electrons. Furthermore, the ZnO nanowires based array had a significantly greater photo current of roughly 58–78% than ZnO NPs sheet and 0.05–0.5 cm^2-s^{-1} diffusivity, which is many hundred times greater than ZnO and Titania NPs films. The polymer co-doped with CuO is utilised to increase electron concentration in polymers reinforced with CF.

The structure of [CF)/(ZnO/ER)/(CuO/ER)/CF] OSCs was designed (Fig. 2). Paper film has been utilised as a separator in OSCs to prevent electron flow produced by the excitation of photons of solar radiation through the surface. It does, however, allow protons to flow through surface of NCs film embedded layers; CF and the CuO-CF.

The prepared NCs films were coated on the top outer surface of OSCs and dried for 24 hours in a drying oven. The pictorial representations of NCs films integration emerged into OSCs are shown in Fig. 2.

Characteristic Studies of OSCs without NCs films

Different electrical characteristics including current-voltage (I-V), and short circuit current (Jsc), open circuit current (Voc) were studied in details to confirm the performance of OSCs.

By analysing the I-V plot under straight sun radiations in normal environment, the I-V character of OSCs without the incorporation of NCs film were explored. The Jsc and Voc may be measured by connecting a multimeter to both parts of the OSCs with wires that have alligator clips which were attached to their ends. The negative electrode (CF/ZnO/ER) was connected to the multimeter's negative terminal, while the positive electrode (CF/CuO/ER) was connected to the multimeter's positive terminal. Voltage and Point to point currents were used to calculate the entire I-V curves. The OSCs has been tested outdoor under the direct solar heat of $32^{o}C$. Figure 5 depicts the experimental set-up for OSCs sans NCs film.

Characteristic Studies of OSCs with NCs films

The I-V properties of OSCs with NCs film integration were examined by measuring the I-V curves in an ambient environment under direct sunshine. The Voc and Jsc can be evaluated by connecting a multi-meter to both sides of OSCs with wires having the alligator clips which attached to their ending sides. The negative electrode (CF/ZnO/ER) attached to negative terminal, and positive electrode (CF/CuO/ER) attached to positive terminal of used multi-meter. Point-to-point current and voltage measurements were then used to calculate the entire I-V curves. The OSCs with ZnO-PVA NCs film have been tested outdoor under direct sunlight at $32^{o}C$.

Results And Discussion

Five different films of ZnO-PVA NCs (Fig. 3a-e) were tested separately with the OSCs to evaluate how the performance efficiency of the OSCs changed at $32^{o}C$ under solar energy. The results of prepared NCs films reveal that increasing the quantity of ZnO NPs leads the organic solar performance improvement to perform worse. This might also resulted in a reduction in band gap of the films. The lowest current density performance implies that a larger proportion of ZnO generates a wire like film in which current flow is hindered, resulting in lesser energy development.

Under direct sunlight, each of prepared NCs films was evaluated separately with OSCs, and the efficiencies produced by the OSCs integrated with ZnO-PVA NCs films are reported in Table 2 based on the performance of thin films of ZnO-PVA of varied compositions. ZnO (1) PVA (6) has the maximum efficiency of 13.57 percent, whereas ZnO (6) PVA (10) has the lowest efficiency of 5.88 percent. The efficiency was affected by a number of factors such as Jsc, Fill Factor (FF), and Voc. Figures 4a-d depicted the percentage of factors influencing the efficiency of OSCs.

The efficiency of OSCs falls as FF drops. As the ZnO percentage in polymer matrix increased, the optical direct bandgap decreased, resulting in efficiency loss. The thickness of NCs films also effects the efficiency of OSCs, with the efficiency dropping as the thickness of NCs films rises.

Performance Study of optimized NCs Films

The optimised film; ZnO(1)PVA(6) with a ZnO concentration of 16.50 wt percent and a PVA content of 84.50 wt percent with an OSCs (Fig. 5) was investigated under 32 ^{O}C solar heat. The performance parameters of the ZnO 16.50 wt% and PVA 84.50 wt% solar thin-film with OSCs have been described in terms of open circuit voltage (Voc), energy conversation efficiency (gec) and current density (Jsc).

The crystalline ZnO can absorb solar energy with an EBG (Eg) of 4.16 eV, which is regarded a remarkable large band gap. In Table 3, it has been shown that the NCs film composed of 16.50% ZnO and 84.50% PVA is an optimal film capable of improving the efficiency of OSCs by almost 4.0 percent. The efficiency of OSC without NCs film was 10.08 percent.

Thin coatings maximize the performance, demonstrating that they function in part as the n-type semiconductors do. As the sun rays hits a NCs film (photoelectrode-absorbing material), the mobile electrons gather energy from this electrode material, and an electron with optimum energy passes through OSCs layer, leaving a vacant position for an electron. The upper ZnO/ER electrode receives the electrons and converts them into energy. By combining with other electron vacancies at the bottom CuO/ER electrode, these electrons complete the circuit.

Conclusion

The solution casting approach was used to successfully manufacture the five films of ZnO-PVA NCs in this work. Each film contains a weight % combination of ZnO and PVA NPs. These films were tested using OSCs to determine the influence of ZnO-PVA NCs layer on OSCs efficiency. The optimized sample, NC-1, achieves the maximum efficiency of 13.57 percent, whereas NC-5 achieves the lowest efficiency of 5.88 percent. The parameters that determine the efficiency of OSCs are Jsc, FF and Voc.

As the FF of OSCs declines, so does their efficiency. As the quantity of ZnO in polymer matrix increased, the optical direct EBG dropped, resulting in efficiency loss. The thickness of prepared NCs film also has an effect on the performance of OSCs, with efficiency falling as the thickness of NCs film rises. The film; ZnO (16.50 percent) PVA (84.50 percent) had the best efficiency among the other samples.

The greatest efficiency of 13.57 percent was discovered, highlighting the potential of NCs films for application in photovoltaic studies to increase the Efficacy of OSCs. To generate a NCs thin film with improved physio chemical properties, the optimal drying time must be found. Future research should focus on improving the deposition quality of ZnO-PVA NCs layer on OSCs in order to make them more appealing in terms of efficiency increase.

Declarations

Competing interests:

The authors declare no competing interests for this research work.

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Tables

Tables 2 & 3 are not available with this version

Figures

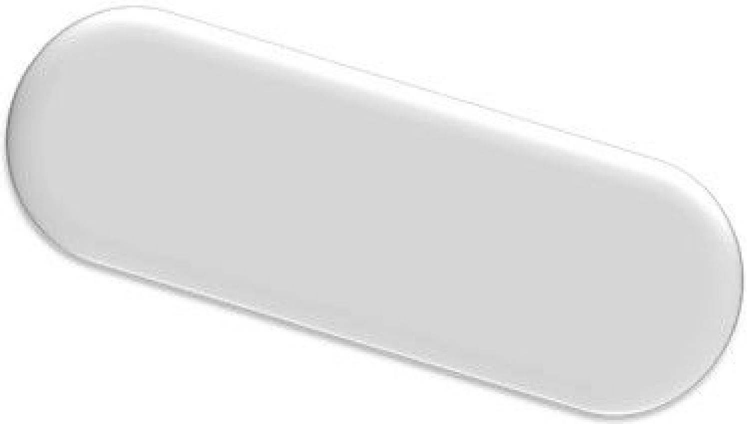


Figure 1

ZnO-PVA NCs film (Proposed Shape)

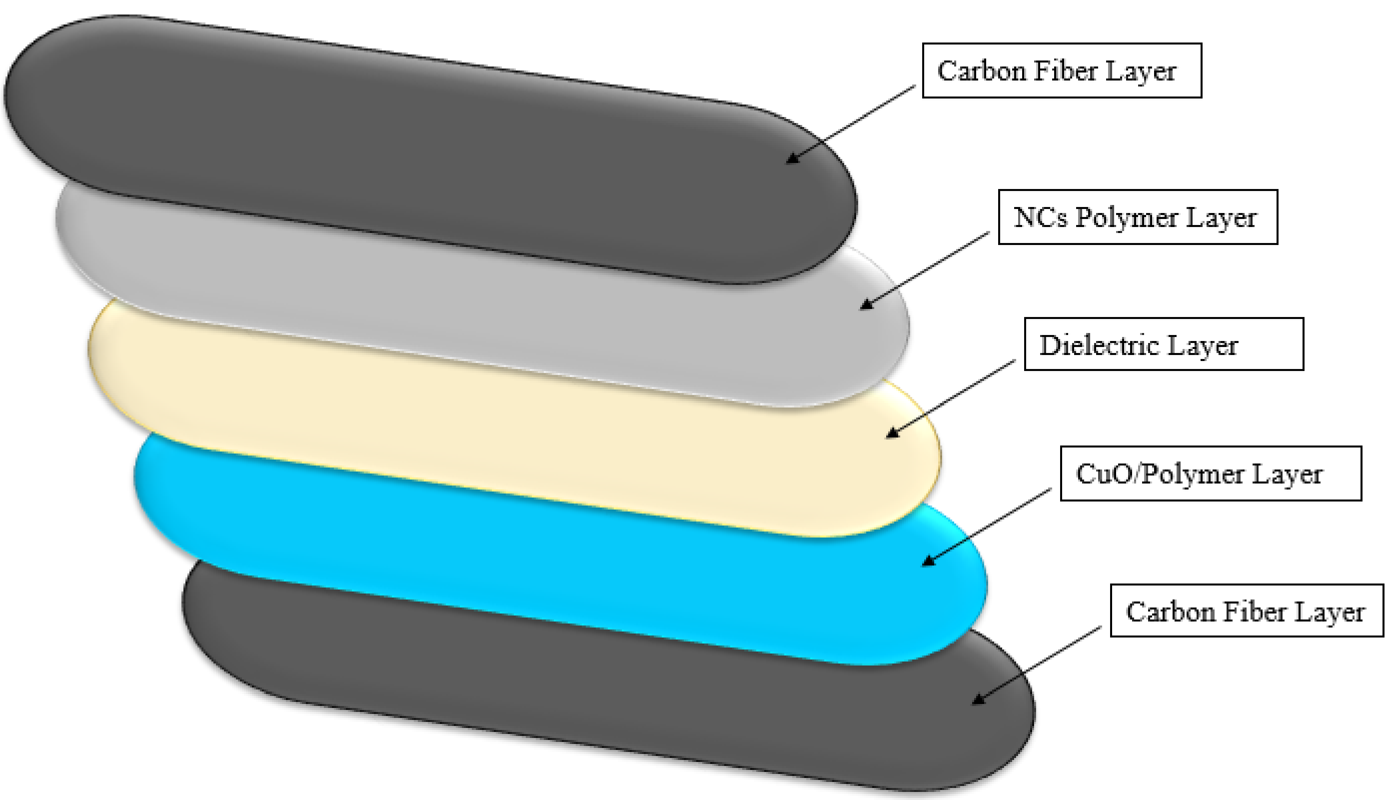
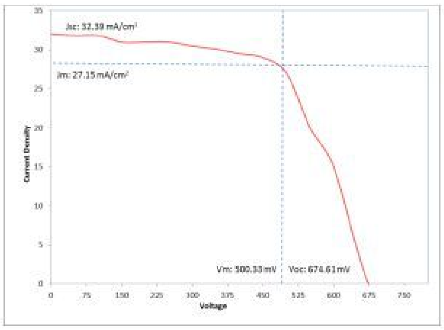
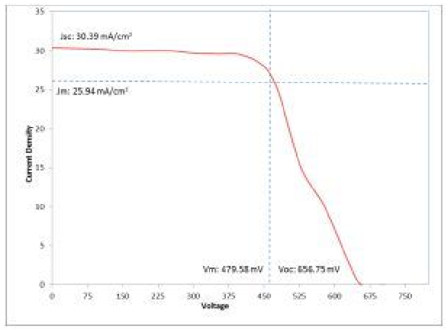


Figure 2

Proposed Architecture of Prepared Solar Cell



(a)



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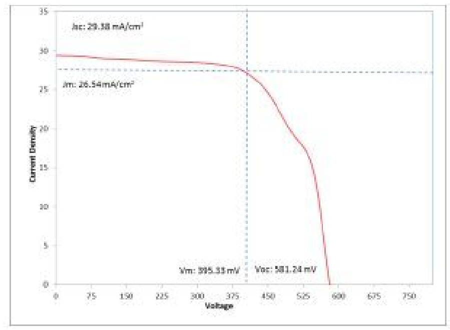

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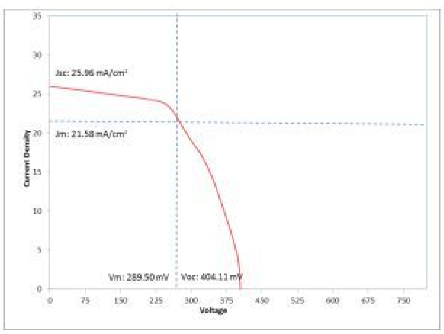

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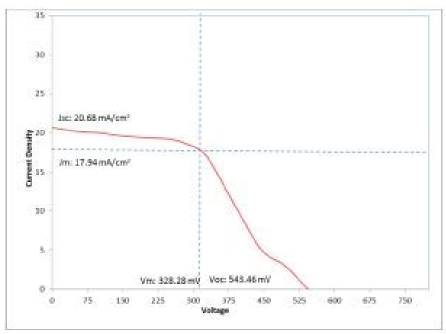

(e)

Figure 3

a: J-V curve of NC-1 film with OSCs at 32^{o}C (solar heat).

b: J-V curve of NC-2 film with OSCs at 32^{o}C (solar heat).

c: J-V curve of NC-3 film with OSCs at 32^{o}C (solar heat).

d: J-V curve of NC-4 film with OSCs at 32^{o}C (solar heat).

e: J-V curve of NC-5 film with OSCs at 32^{o}C (solar heat).

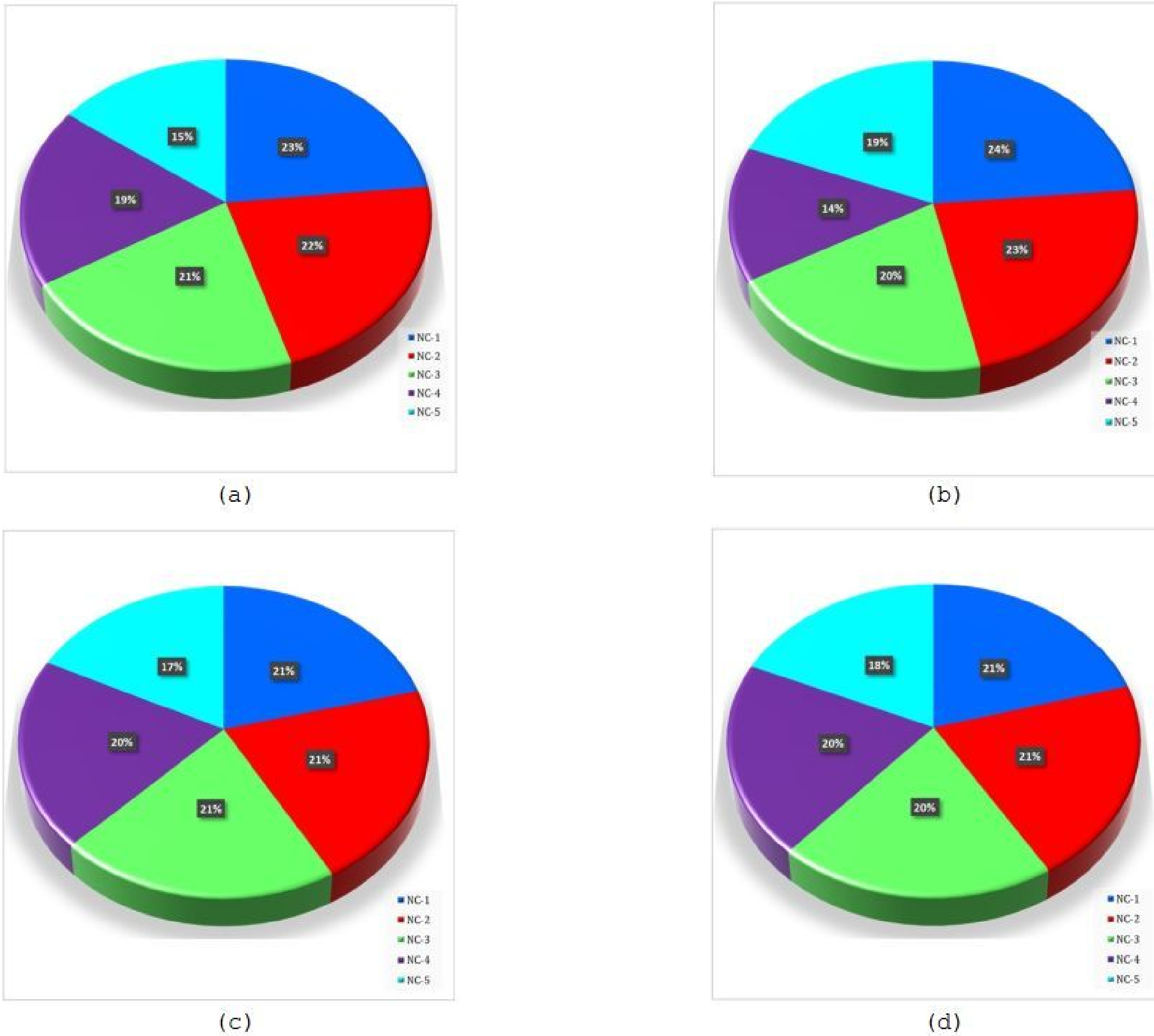

Figure 4

a: Open circuit Density of Prepared OSCs

b: Open circuit Voltage of Prepared OSCs

c: Fill Factor of Prepared OSCs

d: EBG of Prepared OSCs

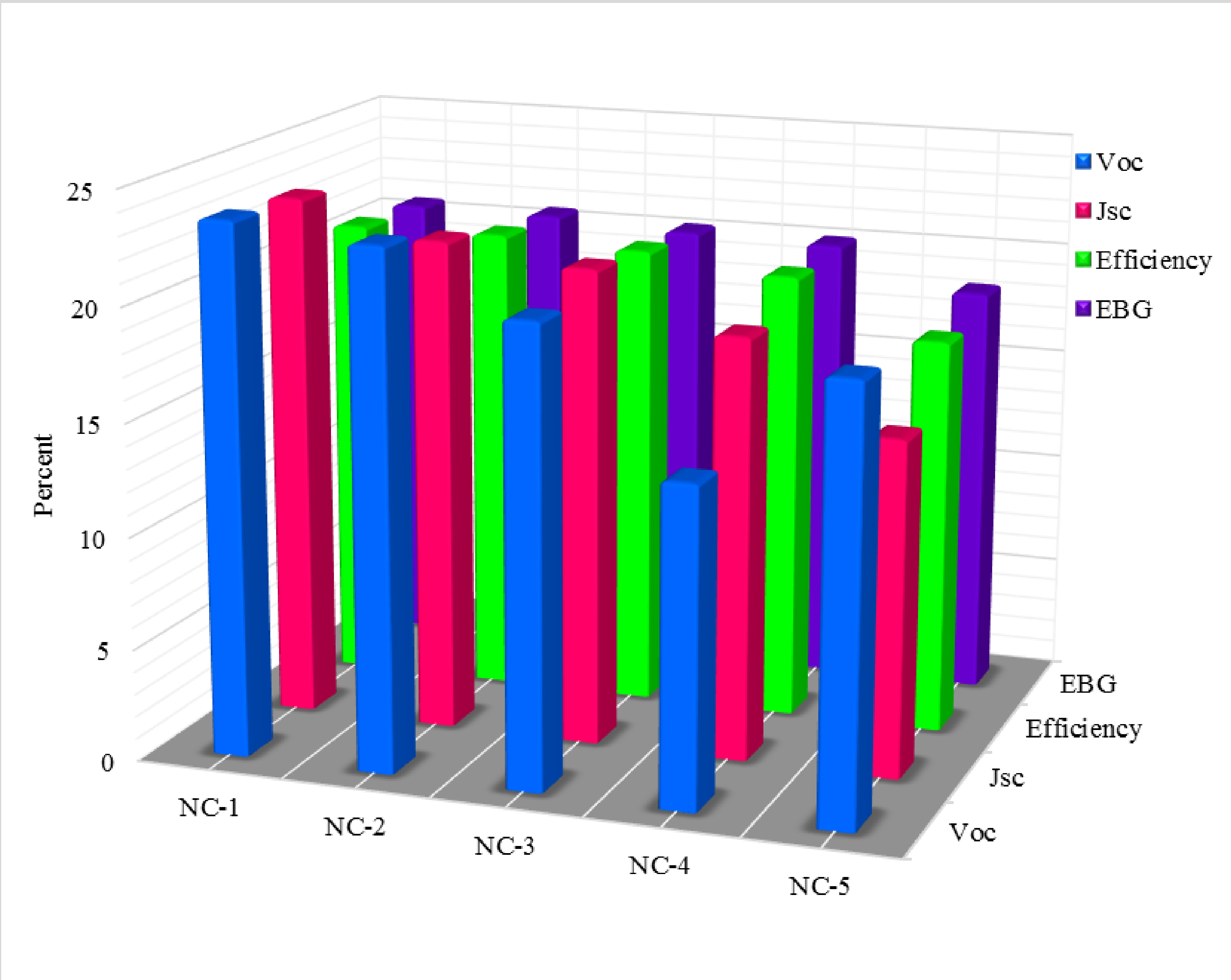

Figure 5

Performance Efficiency Parameters of Prepared OSCs