

## Preparation of Nano-Oxides for Photovoltaic Applications by Drop-Casting

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**Abstract:** The growing demand for sustainable energy has accelerated the development of low-cost photovoltaic technologies based on solution-processed nano-oxide materials. This study explores the fabrication of zinc oxide (ZnO), nickel oxide (NiO), and doped metal-oxide thin films using a simple drop-casting technique for solar cell applications. The films were synthesized via low-temperature chemical methods and deposited as functional layers within photovoltaic architectures, with thickness and morphology controlled through precursor concentration and annealing optimization. Structural, optical, and electrical properties were characterized using XRD, SEM, UV-Vis spectroscopy, and current-voltage (J-V) measurements under simulated solar illumination. The results show that controlled annealing and suitable doping improve crystallinity, reduce defect density, and enhance charge transport. Doped NiO layers provide better band alignment and reduced interfacial recombination, while ZnO nanoparticle films demonstrate effective electron transport and improved interfacial contact, leading to enhanced power conversion efficiency and device stability. These findings confirm that drop-casting is a cost-effective, scalable approach for producing high-quality nano-oxide thin films for next-generation photovoltaic applications.

**Keywords:** Photovoltaics, Nanooxide, Dropcasting

### Introduction

The constantly increasing energy needs in the world and the necessity to create sustainable solutions have moved solar energy to the foremost of the renewable power technologies [1]. The third-generation solar cells which are characterized by the new material compositions are among the approaches of harnessing solar energy that have received a lot of attention owing to their ability to yield higher efficiency and cost-effectiveness in energy conversion [2]. Incorporating such advanced photovoltaic technologies as dye-sensitized solar cells, organic solar cells, and perovskite solar cells, these technologies use low-cost and abundant materials, and scalable fabrication methods, making them suitable to a wide range of applications, such as portable electronics, and ambient energy harvesting to Internet of Things devices [3]. A promising fabrication technique to these new solar cell technologies involves drop-casting, which is a technique that has simplicity, is inexpensive, and adaptable in depositing thin films with desired morphology and thickness [1]. This technique enables the accurate positioning of materials e.g. zinc oxide nanoparticles, needed to maximize light absorption and electrical transport in solar cell devices [4], [5]. The emphasis on affordable and simple approaches such as drop-casting is further motivated by the fact that it can be applied to mass-produce solar cells offering a pathway for overcoming the high-temperature processing limitations, frequently related to traditional metal-oxide photoanodes such as titanium dioxide [6], [7]. A new generation of photovoltaics is achievable through the integration of nanostructured metal oxides, especially those synthesized by facile chemical co-precipitation, giving universal platform to optimize the photoanode materials [8], [9]. It will also be determined in this review how drop-casting can be used to prepare nano-oxide layers e.g. those derived from ZnO and TiO<sub>2</sub> nanoparticles and the effect of the synthesis methods on the characteristics of the material and the subsequent photovoltaic performance [10], [11]. In particular, the paper will investigate synthesis of zinc oxide nanoparticles with a particular focus on their characteristics and the effects the synthesis pathways have on their use in the third generation solar cells, as well as discuss the issue of their possible toxicity [12]. Moreover, the characterization of the synthesized nano-oxides will be also analyzed in terms of structural, optical as well as electrical properties to establish the correlations between the properties of the materials and the performance of the photovoltaic devices. Finally, the work is the one that is expected to emphasize the effectiveness of drop-casting in the creation of effective and stable perovskite solar cells based on low-temperature solution-processed zinc oxide

nanoparticles, which will become a feasible alternative to the conventional electron transport layers [13]. This method increases not only the interfacial contact in perovskite solar cells but also helps to overcome the chemical instability of zinc oxide in contact with perovskite layers and, as a result, contributes to the enhancement of the stability of the devices and their efficiency [14], [15], [16]. Considering the importance of nanocrystals as performance-enhancing materials in solar cells, the incorporation of functional layers as efficient layers can cause significant improvements in charge transport, and interface modification that will result in an increased power conversion efficiency and stability [17].

## Literature Review

This review provides a critical analysis of the present state of using nano-oxides, namely zinc oxide and nickel oxide, in photovoltaic devices, discussing different synthesis techniques, and how they affect the properties of the materials and the performance of the device. Nanocrystals, such as those on the basis of zinc oxide, have been broadly accepted to their unique characteristics as well as potential application in new-generation optoelectronic devices, not only as efficient light harvesters, but also as important functional layers for interface modification and charge transport in highly efficient solar cells [17]. Aqueous processes, such as the preparation of zinc oxide nanoparticles, can be used to produce cluster-free solutions, which can be drop-cast to produce high quality thin films [18], [19]. This method can be especially valuable in applications, including electron transport layers in perovskite solar cells, where material purity and morphological control are the two most important factors to achieve high performance [20]. Moreover, the increase in the surface area afforded by smaller nanoparticles in such layers can greatly increase the capacity of charge collection in the device [19]. Zinc oxide nanocrystals can be used in multiple ways as electron transport layers in traditional and inverted solar cell structures to enable considerable enhancements to device performance and environmental stability by means of optimized hole-blocking and decreased interfacial charge recombination [21]. On the other hand, some metal oxides such as NiO, Ti-doped MoO<sub>2</sub>, Co<sub>3</sub>O<sub>4</sub>, Cu<sub>2</sub>O, CuCrO<sub>2</sub>, and CuGaO<sub>2</sub> have been observed to be superior top hole transport layers in perovskite solar cells with high performance, making them highly effective in reducing non-radiative recombination at surface because of their capability to mitigate the effects of high surface trap densities in nanocrystalline materials [17]. Nickel oxide nanoparticles doped with zinc have also been utilized as hole transport layers to enhance the performance and stability of perovskite solar cells, and their physical and morphological properties have been fully investigated with the use of X-ray photoelectron spectroscopy and scanning electron microscopy [22]. In this way, it is found that crystallographic orientation and grain boundary characteristics are likely to affect the carrier mobility and efficiency of charge extraction with direct effects on the overall photovoltaic performance [23]. The metal-oxide nanoparticles such as ZnO and NiO<sub>x</sub> as charge-carriers in organic and hybrid organic-inorganic perovskite solar cells elaborates their functionality and importance in modern photovoltaic design [24]. These materials are significant in the control of the charge extraction and transport and hence have influence on the overall power conversion efficiency and long convergence stability of the devices. This is based on the fact that they can provide strong and stable surfaces with the active layers that is coupled with controllable electronic properties that are needed in attainment of high performance solar energy conversion [25].

## Methodology

The steps that are followed in the synthesis as well as characterization of nano-oxide based materials have been explained in this section with clear references being made towards the drop-casting method of thin film deposition followed by production of the photovoltaic device. This method entails precursor selection, solution preparation, which includes particular areas of deposition of drop-casting process, and the annealing steps required in the achieving the best film morphology and crystallinity as proposed by the research which provided the best quality of film and surface roughness through the optimization of solution processing parameters of copper-doped nickel oxide films [26].

The solvent, concentration of the precursor and environmental conditions used during drop-casting are important parameters that determine the homogeneity, thickness and porosity of the nano-oxide layers deposited. Such parameters are highly inspected in the way that defects are absent in the formed

films and are also characterized with better charge transport properties. The structural, morphological and topographical features of films synthesized following deposition are then determined using characterization methods like X-ray diffraction, scanning electron microscopy and atomic force microscopy [22], [27], [28].

In addition, optical methods of characterization such as UV-Vis spectroscopy and photoluminescence measurements are employed in determining optical band gap of the films, light absorption ability and charge carrier dynamics which are essential in determining the photovoltaic performance. The fabricated photovoltaic devices are electrically characterized, i.e. current voltage measurements in simulated solar light conditions, in order to provide the most important performance indices, including open-circuit voltage, short-circuit current, fill factor and power conversion efficiency.

Moreover, impedance spectroscopy, transient photocurrent/photovoltage will also bring out additional information on charge transfer kinetics and recombination processes within these devices. This is an efficient form of analytical study which is highly effective in examining the complicated association among the material properties, processing variables and the ultimate photovoltaic performance of the devices.

There is also the need of numerical simulations that help study the physical processes in these solar cells in order to visualize the optoelectronic properties and can optimize the design on the basis of analysis of J-V characteristic, spectral response and energy band structures [29].

Such simulations are essential in making estimates on how many material compositions and architectural designs including integration of Ni-doped CuO layers can affect the efficiency and stability of the devices and therefore in the direction of experimental work to produce the optimal device fabrication [29].

## Results

This section will give a report of experimental work performed, i.e. the specifics of the synthesized nano-oxide materials and their performance in photovoltaic devices. Particularly, it will involve an analysis of the structural, morphological, optical, and electrical characteristics of the nano-oxide thin films, and their power conversion efficiencies and stability as photoconductors in solar cells. The study includes pure and doped nano-oxides and particularly methods of doping such as the copper in nickel oxide in order to enhance the characteristics of materials to enable the photocatalytic activity and the general photovoltaic performance to be optimized [30]. One good example is copper oxide, which has been actively studied as a hole-transporting material in inverted planar heterojunction perovskite solar cells due to its intrinsic p-type conductivity, high-mobility characteristics and positive energy band alignment with perovskite absorbers [31].

The facile synthesis of pure and metal-doped copper oxide nanoparticles through low temperature, hydrothermal techniques is yet another illustration of their suitability in various, photovoltaic uses, such as solar panel windows [32]. In addition to copper oxide, nickel oxide is also a promising p-type material, having a high conductivity, switching speed, and redox kinetics that can be used as an effective hole extraction layer in perovskite solar cells [23], [33]. It's chemical stability and cost-effectiveness making it even more clear why it can be used as an alternative to standard organic hole-transporting materials, particularly large-scale production [34]. Often further photovoltaic effects are achieved by combining nickel oxide with other metal oxides, e.g. in Cu:NiO combinations, to optimize charge extraction, minimize energy band mismatches, as shown in computational studies of ternary devices [35]. This involves the analysis of the effect of the thickness of the NiO layer on the efficiency of power conversion, and a study has been carried out to show that the efficiency increases uniformly with increasing the thickness of the HTL layer [36]. Furthermore, the temperature of the calcification process has a significant impact on the crystallinity and surface morphology of NiO films where a high temperature of the process often results in higher crystallinity, at the cost of surface roughness [23], [37].

An annealing of nickel oxide films at 300 °C revealed some smaller and more homogeneously dispersed particles compared to those annealed at high temperatures, which indicates a weak correlation between thermal processing and morphology of the films [23]. Copper addition to nickel oxide (Cu:NiO)

has also been found to induce structure orientation to form multiple crystallographic planes and reduce the concentration of Ni<sup>3+</sup>/Ni<sup>2+</sup> ratio, without maintaining the natural NiO-like structure [38].

This is a structural modification, alongside the gain of conductivity and working functionality due to doping that greatly help in extracting holes as well as selectivity of the charge in the perovskite solar cells, and, the rate of charge recombination decreases, and the power conversion efficiency gets enhanced [39].

It is also interesting to note that NiO is highly catalytic and has a high interaction with ions in the iodine based electrolyte which implies that it would be desirable target as a counter electrode in Dye-Sensitized Solar Cells and as an effective hole transport material in perovskite solar cells [2].

## Discussion

The discussion section will be centered on how these findings could be interpreted within the larger framework of the already existing literature and theoretical frameworks, what processes occurred that lead to the improvement of the performance of the devices. This makes it quite accurate how the structural changes, that is an increase in crystallinity and a decrease in the density of the defects, lead to the improvement of optoelectronic properties, and eventually the increased power conversion efficiencies to the devices made [23].

The annealing temperature also plays a critical role in enhancing these properties in the 700 °C that enhances the development of a superior interfacial bond, repositioning of the atoms, but excessively high temperatures that cause cracking and melting of the films [40]. This subtle balance is an indication that there must be a control over temperature when preparing such films in order to guarantee the best material characteristics [40].

Additionally, integration of dopants, e.g., lithium, to NiO films are imperative throughout the procedure of controlled electronic band structure and advanced mobility of the holes, and this also improved charge transport in the device structure. These doping mechanisms particularly using such components as cobalt and lithium to enhance the performance of NiOx based hole transport layers have been reported very successfully to produce high power conversion efficiencies and stability of the device in the perovskite solar cells [39].

The careful selection and optimization of doping levels are important, and the presence of too much doping may result in the creation of defects to counteract positive effects, causing device performance to be worse [41]. The careful engineering of deposition parameters, including pressure and annealing are also crucial to realizing high-transparency and moderately conductive thin films of NiO that can also be used as effective hole transport layers and window layers in inverted perovskite solar cells [42]. The optimized films have a high optical transparency and electrical conductivity directly proportional to the increased photocurrent density and the overall performance of the device [42]. For instance, increasing the annealing temperature of NiO quantum dots to 700 °C has been shown to reduce crystallite size and eliminate pinholes, leading to superior performance as a hole transport layer [40]. On the other hand, the post-annealing treatments may decrease the carrier concentration and at the same time enhance the mobility of NiO films, which is important in maximizing charge transport and gain greater power conversion efficiencies [43].

## Conclusion

The synthesis parameters, in particular, calcification temperature and doping mechanisms, are highly critical in controlling the optimum of the structural and optoelectronic properties of nickel oxide nanomaterials in the high-performance photovoltaic applications. This close control enables the fabrication of good hole-transport layers, which improve charge extraction, and reduce recombination losses in perovskite solar cells, which enhances the overall power conversion efficiency. Future research activities in this field should be directed to explore new doping material and other fabrication techniques to advance the boundary of the NiO based HTL in terms of performance and stability particularly in regards to large scale production and long operational reliability. Manganese doping has been demonstrated to improve conductivity and charge transfer capability of NiOx resulting in improved short-circuit current density and stability of the entire device in perovskite solar cells [44]. On the same

note, the concentration of NiO nanocrystal solutions can also be optimized to have a substantial impact on the properties of hole transport materials and the power conversion efficiency of PSCs, and high-quality films have been realized by careful concentration control [39]. Further, it has been shown that the quality of the ligand-protected colloidal NiO nanocrystals can be used to produce hole transport layers of pure composition, free of impurities, which is essential to maximize their electrical and optical properties, and ultimately device efficiency [39]. In addition, nanocomposite methods can fine-tune the work function of NiOx films, e.g., the incorporation of strong electron acceptors such as F4-TCNQ, allowing the ideal level of energy alignment to a range of organic donor materials in photovoltaic cells [45]. These state-of-the-art plans highlight the current attempts to refine NiO as a high performance and versatile material to support next generation photovoltaic technologies. In addition, non-stoichiometric behavior of NiO, which is characterized by the existence of Ni<sup>3+</sup> ions, tends to be associated with an increase in the p-type conductivity and the darker color and has the potential to tune electrical properties and use controlled oxidation states [23]. The future effort on the optimization of NiOx thin film preparation technique may look into several morphologies and structure to enhance light transmittance, conductivity and film quality in addition to minimizing the defect density to enhance performance of the device [46]. Additionally, the exploration of hybrid organic-inorganic doped NiOx nanoparticles presents a promising route for developing highly conductive hole transport layers with tunable work functions, essential for optimizing charge extraction in inverted device structures and achieving enhanced solar cell efficiencies [47]. To further enhance the hole-extraction capability of the NiOx layer, researchers have synthesized molecular TCNQ derivatives with controlled electron affinity to dope the precursor solution of NiOx nanoparticles [48].

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