Fabrication of solar cell using titanium, zinc, carbon and gold nanoparticles

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Abstract. Gold, titanium dioxide, zinc oxide, and carbon nanoparticles each have characteristics that can be used as the active, electron transport, and hole transport layer in a solar cell. Nanoparticle based solar cells have emerged as a good substitute for silicon solar cells. They cost lower to manufacture, as compared to producing solar cells with crystalline semiconductor material. This is because the nanoparticles can be synthesised at room temperature, while silicon solar cells need to be made using high temperature vacuum deposition method. In this research, the nanoparticles will be synthesised using submerged glow discharge plasma. After synthesis, the nanoparticle products were analysed using scanning electron microscopy to determine their size and shape. The solar cell will then be fabricated in multiple configurations. Testing on these multiple solar cells will be done under direct sunlight to determine if the cells work and how each material affects the cell.

1. Introduction
Silicon solar cells are commonly used as a source of renewable energy. They are reliable and have the highest efficiency among all other alternatives. Even so, nanoparticles-based solar cells have become a promising substitute. They have a lower manufacturing cost as compared to conventional silicon solar cell. This is because the nanoparticles can be synthesised at room temperature.

Recent studies have shown that metal nanoparticles such as gold nanoparticles absorb and scatter light based on localized surface plasmon resonance (LSPR) [1]. By incorporating these characteristics with other materials such as titanium dioxide, zinc oxide, and carbon, it is possible that a solar cell with an efficiency of 50% or more will emerge. This research focuses on using submerged glow discharge plasma (SGDP). This method is relatively new and has not been widely used in the synthesis of nanoparticles for solar cells fabrication.

2. Literature review

2.1 Submerged glow-discharge plasma setup (SGDP)
SGDP is a useful and straightforward because non-equilibrium plasma provides fast reactions at atmospheric pressure [2]. When an external energy source is connected to the system and power is supplied, the neutral gasses in the solution are ionized. Electrons are freed from their covalent bond due to the excess energy and plasma is generated. The plasma creates a strong electric field as it has an equal number of negative electrons and positive ions. The material that is to be reduced to nanoparticles will be connected to cathode, while the material that will supply electrons will be connected to the anode.
Figure 1. Submerged glow discharge plasma (SGDP) method

There are 4 stages of reaction using the SGDP; electrolysis, vaporization, transition, and full plasma stage [2]. During the full plasma stage, the high heat of the plasma partially melts the cathode surface to produce nanoparticles. After some time, as the current flow concentrates on the current spot, the plasma near here will be heated extra by added Joule heating and melts away or ionizes the rest of the cathode and the reaction continues as long as a stable voltage is supplied. Molten metal will cool down immediately in the electrolyte and form fine spherical particles.

Since the nanoparticles synthesized from SGDP have nearly uniform shape and size, it is highly advantageous to explore the possibility of fabricating an all-metal nanoparticle solar cell. The following sections describe the candidate nanoparticles and their role as solar cell materials.

2.2 Titanium dioxide nanoparticles

Titanium dioxide (TiO₂) is a dielectric material with its bandgap in the range of 3.0-3.2 eV. This means it is a wide bandgap semiconductor that has strong absorption of high energy photons. It is also transparent to photons with energy (hv) that have bandgap energy (Eg) in the range of 1-2 eV [3]. TiO₂ also has a high reflective index, up to n=2.5, that enhances the solar cell short circuit current density, Jsc [4]. Besides that, it can also be used as an electron transport layer (ETL) in the solar cell. TiO₂ is currently widely used as ETL in perovskite solar cells (PSCs) due to its high electron mobility. This was observed in the case of P3HT:PC₆₁BM perovskite was used as an active layer. The device that had no ETL showed optimum efficiency at just 1.94%, while the device that had TiO₂ ETL performed at 4.29% [4].

2.3 Zinc oxide nanoparticles

Zinc oxide (ZnO) has very good tuneable optoelectronic properties and is a widely used transparent conductive oxide. ZnO is used as a hole blocking layer for perovskite solar cells. It efficiently reduces the recombination of electron and hole pair at the perovskite/fluorine doped tin oxide (FTO) interface [5]. By reducing the recombination rate, more electrons will move towards the P-type side of the solar cell and thus more electricity is produced. The efficiency will then increase, such as in the case of a perovskite solar cell with glass/FTO/ZnO layers had a maximum efficiency of 14.2% [5]. ZnO, similar to TiO₂ is also widely studied and used as an electron transport layer. Both have similar bandgap value at 3.2 eV, but ZnO has much higher electron mobility, around 115-155 cm²/Vs² [6].

2.4 Gold nanoparticles (Au NP)

Au NP has two great properties that helps increase the efficiency of a solar cell. They improve the absorption efficiency of the photovoltaic layer. Au NP that are placed above the photovoltaic layer that provides an angular spread which increases the effective light path and therefore, the absorption, this term is called light scattering. They can also facilitate light concentration. Au NP is embedded in the photovoltaic layer. The presence of an intense local field on the surface of the Au NPs increases the
sunlight absorption. Besides that, Au NP has a spectroscopic feature known as surface plasmon resonance, giving it good energy absorption in the visible light range. This feature comes from a collective resonant oscillation of the free electrons in its conduction band [7]. The absorption is also reliant on the shape and size of the particle. Spherical shaped particles 60nm and below showed much better light absorption than scattering. Besides that, a TiO2-Au nanocomposite can be fabricated as an active layer due to their enhanced plasmonic resonance and light absorption.

2.5 Carbon nanoparticles (CNPs)

Solar cells fully made out of carbon nanoparticles have also been fabricated, but their efficiencies are somewhat subpar at 0.46% being the champion efficiency [8]. For this research, the CNPs will be used as the hole transport layer (HTL). Single walled nanotubes (SWNTs) have emerged as an effectively substitute to the commonly used PEDOT:PSS as the HTL between photoactive layer and indium tin oxide glass for perovskite solar cells. The results showed that 12.2nm thick layer of SWNTs had better performance as compared to PEDOT:PSS. Graphene oxide has also been predominantly used as OPV devices’ HTL, but they are difficult to produce and are not cost effective. CNPs have been tested as an alternative to the expensive hole-transporter spiro-OMeTAD in the configuration of FTO/TiO2 mesoporous CH3NH3PbI3-xClx/CDs/Au [9].

A solar cell made of only metal nanoparticles have shown to work before, in the example of heterojunction solar cells that is made of di-copper oxide, zinc oxide and titanium oxide, and gold nanoparticles. They have shown to provide an efficiency of 0.25%, FF of 0.33, JSC of 2.7mAcm-2and VOC of 0.28V [10].

3. Nanoparticle synthesis

Figure 1 shows a 300ml glass beaker with 200ml of 0.1M potassium carbonate (K2CO3). Titanium/gold/zinc wire of 0.5mm in diameter and exposed length of 50mm, silver (Ag) wire/carbon rod of 1mm with a diameter of 1mm and same exposed length, and a thermometer are dipped in it. Titanium/gold/zinc/carbon wire is connected to the negative output of the DC power source, making it the cathode which will be dissolved. The Ag wire on the other hand is connected to the positive output, and thus making it the anode. The anode and cathode were cleaned by dipping them in 10% sulphuric acid for 10 seconds, then washed with distilled water.

The voltage is initially set at 5 volts to heat the electrolyte for 60 minutes. After that, the voltage is increased by steps of 5V every minute until the glow can be seen. The voltage is then maintained for the production of the nanoparticles. The voltage to reach glow discharge for this experiments materials are 95V for Zn, 120V for Ti, 100V for C, and 125V for Au.

3.1 Nanoparticle collection and analysis

After SGDP, the products will be collected by centrifuging for 10 minutes. The product will then be washed down with distilled water to remove the electrolyte. The nanoparticles will be sent for Scanning Electron Microscopy (SEM) to identify the elemental composition and map each type of nanoparticle.

4. Fabrication of solar cell
Figure 2. Proposed fabrication route for nanoparticles-based solar cell.

4.1 Step 1: Base preparation (Cathode)
The conducting side of ITO (indium tin oxide) glass can be determined by using a multimeter. The coated side is the one that shows low resistance. The coated side is faced upwards and a quarter of its surface area will be covered with adhesive tape.

4.2 Step 2: Electron transport layer (ETL) preparation
The electron transport layer (ETL) ZnO nanoparticles is deposited on the exposed surface and spread evenly using a dropper and a spin coater. The glass plate is placed on a hot plate at 350ºC for 20 minutes. The hot plate is turned off while waiting 10 minutes before removal. Heat treatment is done to ZnO to increase the surface roughness and also particle surface area. The absorption of light in the 350-700nm wavelength region will be increased [11]. The ZnO layers that are sintered at 300-400ºC showed a homogeneous distribution of closely packed, grouped nanoparticles. The heating has no effect on the size of the particle or the porosity of the layers. Oxide particles are more likely to grow at these temperatures and thus reducing the grain boundary.

4.3 Step 3: Active layer
The Ti-Au nanocomposite layer will be the active layer. Two to three drops of it will be added atop of the prepared ETL. The spin coater is used to evenly coat the layer. This layer should be around 30nm thick for maximum efficiency. The hot plate is warmed to 300ºC and the glass plate sintered on it for 5 minutes. This is to remove any excess methanol or water that is present in the composite material.

4.4 Step 4: Hole transport layer (HTL) preparation
Carbon NPs are placed on the active layer to facilitate hole transport. The layer is made using the droplet and spinner but no additional heating is required. This layer will be harder to smoothen out as the NPs are coarse, thus the layer will be verified for smoothness after spin coating.

4.5 Step 5: Electrode layer
The Au layer is deposited on the HTL or the active layer and acts as the electrode for the cell, which helps to hold the holes that will recombine with the incoming electrons from the cathode. This layer is prepared similar to the previous steps. However, heating is not required.

4.6 Step 6: Top preparation (Anode)
After all layers have set and dried, another ITO glass plate with the conductive side facing down is then placed upon them. The ITO plates will be placed laterally as shown in Figure 2 to facilitate good electrical contact, and avoid short circuiting. Two binder clips are used to keep the ITO plates in place and the tape from step 1 is removed to expose the rest of the ITO. Even though Au is a very good conductor, this ITO plate is added so that no sunlight exposed area of the cell is blocked and power conversion is maximized, also protecting the Au layer from smudging during testing.
5. Results and discussion

Figure 3. SEM images of (A) ZnO NPs (B) TiO$_2$ NPs (C) Au NPs (D) C NPs

The synthesized nanoparticles are shown in Figure 3. All nanoparticles were spherical shaped. Because of this shape, they will have good absorbance of light and improve the efficiency of the solar cell.

A prototype solar cell was fabricated using copper oxide, titanium oxide and zinc oxide nanoparticles sandwiched between two ITO glass plates measuring 20mm by 20mm. The prototype was exposed to sunlight at midday. To eliminate heating effect, the sunlight exposure was repeated several times in quick succession. Using a multimeter, the voltage measured was 0.25V, while the current was 0.005mA. When the prototype was removed from sunlight, the voltage and current measurements dropped to zero almost immediately. Although the photocurrent generated was small, the experiment has shown that the prototype solar cell could generate electrical current when exposed to sunlight. Further experimentation will be done on fabricating the solar cell to determine its feasibility and to determine the efficiency.

6. Conclusion

The proposed solar cell using a combination of titanium, zinc, carbon and gold nanoparticles have the potential to generate electrical current under sunlight exposure. The addition of carbon as the hole transport layer, and TiO$_2$-Au nanocomposite layer to exploit its plasmonic resonance would enhance the efficiency of the solar cell. Submerged glow-discharge method was used to produce the nanoparticles, and is found out to be a good substitute instead of using other synthesizing methods. Initial testing using a prototype solar cell has shown that the fabricated solar cell generated electricity mainly by photoelectric effect and not due to thermoelectric effect from the sun. The efficiency of the cell could be improved by using more sophisticated methods, or more refined nanoparticles, but overall this is a good stepping stone for future works. This type of solar cell is promising for future development not only because of it being economical but also due to its environmentally friendly synthesis method.

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