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Photovoltaic Characteristics of Amorphous Carbon Homojunction from Biomass by Simple Method

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ABSTRACT

Amorphous carbon homojunction have been successfully made from the palmyra sugar. Sample junction are made two configuration p-n and p-i-n on a glass substrate ITO. Samples junction were deposited using the nano-spraying method. Where p, n and i layer were made from boron, nitrogen and un-doped amorphous carbon, respectively. The thickness of each layer tested using SEM is in the order of hundreds of nanometers. The samples shows an increase in current and voltage value when illuminated with light compared dark condition. The relationship between current and voltage at p-n junction shows are curve that meets the rules as rectifier. When the sample junction is tested with direct sunlight at AM 1.5 conditions, it shows current and voltage relationship that meets the rules for the emergence oh the photovoltaic effect. The sample p-n junction shows maximum efficiency value of 0,0175% while the p-i-n junction shows 0,0705%. Both sample show that they are can function as solar cells. Sample p-i-n junction work better than p-n junction.

Keywords
Photovoltaic, Amorphous carbon, Palmyra sugar.

Introduction

In this decade the world's population has increased rapidly resulting in an increase in the need for energy. Energy needs are currently from fossil based-energy. Fossil fuel are limited in supply and cause pollution with the CO_2 they produce. This increases the interest researcher to develop non- fossil energy. The suns as the largest energy source emits 1.2. 10^{17} watts at earth's surface. Solar cells convert solar energy into electrical energy directly. Commercially the active materials for solar cells is dominated by crystalline silicon. However, crystalline silicon-based solar cells are relatively expensive compared to the electrical energy are produced and are less friendly to the environment during the fabrication process. Carbon is element that is in the same group as silicon has the same characteristics based on its valence electrons [1].

Carbon differs from silicon in its hybridization. Silicon has sp^3 single hybridization while carbon has sp, sp^2 and sp^3 hybridization. There are 3 forms are carbon, namely diamond when it has 100% sp^3 hybridization, graphite when it is sp^2 100% and amorphous carbon when it is mixture of sp^2 to sp^3. The electronic characteristics of carbon depend on the percentage of hybridization. Graphite is crystalline and act as conductor while diamond is crystal of carbon which acts an insulator. Amorphous carbon is the most important form of carbon in many applications. Amorphous carbon can act as a conductor, semiconductor and insulator. The electronic characteristics of amorphous carbon depend ratio of sp^2 and sp^3. The energy gap is the range 0 – 6 eV depending on the percentage of sp^3. Graphite with 100% sp^2 has zero energy gap while diamond with 100% sp^3 has an energy gap 5,5 eV. The energy gap can be adjusted by adjusting the hybridization [2,3].

Carbon has a high potential to developed as an active photovoltaic material. Amorphous carbon film has a higher absorption of sunlight than amorphous silicon at the same thickness. Absorption of sunlight and the resulting photocurrent can be adjusted through the hydrogen content and density [4]. A thin film of amorphous carbon was deposited using modified CVD with palm oil as a precursor. The film were deposited on glass and p-type silicon substrate with a deposition time 1 hour and temperatures varying from 350^0 to 550^0. The optical band gap shows stability in solar cell application at deposition temperature 400^0 and 350^0 with a value of 0.7 and 1.4 eV [5]. Amorphous carbon doped with nitrogen has been successfully deposited using CVD with ethanol as a precursor with nitrogen gas as the doping source. The a-C:N films were deposited on a glass substrate with temperatures varying from 250^o to 550^o. The electrical conductivity of the film is within the range of semiconductor materials. The a-C:N film shows a response to the photon that hits it by creating a pair of electron and holes [6].

Carbon has a high potential for application in photovoltaic technology, but carbon homojunction solar cells have not been developed significantly. The development of carbon solar cells is dominated by heterojunction carbon with silicon. Using AACVD with camphor oil as precursor carbon heterojunction solar cells have been made. Nitrogen gas as a doping source to form an n-type semiconductor. Solar cells with Au/n-C:N/p-Si/Au configuration with deposition temperatures varying from 500 to 650 ^{0}C resulted in efficiency from 0.0002 to 0.001% when tested with solar simulator at condition of AM 1.5. While in the Au/p-C/n-Si/Au configuration, the efficiency is 0.000048% with pure a-C being used as a p-type layer [7]. Heterojunction carbon solar cells with camphor oil precursor using AACVD deposited on n-type silicon substrate have been successfully fabricated. The p-type carbon layer was deposited within 0.5 hours to form Au/p-C/n-Si/Au solar cell configuration resulting in an efficiency of 0.008% [8]. A p-i-n junction heterojunction solar cells has been developed with layer p-type made of polymeric amorphous carbon with an optical band gap energy of 2.7 eV. Solar cell with p-PAC/i-*a*-Si:H/n-Si:H with a p-PAC thickness of 5 nm. All layer were deposited using PECVD on a glass substrate. The test result under AM 1.5 conditions showed a photovoltaic effect with an efficiency of 3.8% [9].

A carbon solar cell with the configuration of Al/C_{60}/*a-C*/ITO glass has been successfully made, where the *a*-C layer is deposited using a remote plasma cracking. Layer *a-C* function as p-type while C_{60} function as n-type. C_{60} is exposed to N_2 in a vacuum during the sublimation process to form n-type. Two sublimation temperatures are applied namely 450 and 500^{o}C. The efficiency of solar cell produced is 0.021 and 0.0085% [10]. Heterojunction solar cells have been fabricated using CVD, the carbon layer is deposited on n-Si substrate. The layer a-C was deposited at a temperature 400^{o}C to form a solar cell with *a-C/n-Si* configuration. Two samples of solar cells were measured for their output power efficiency. Sample *a*-C/n-Si and *a*-C/n-Si with HNO_3 treatment. The resulting output power efficiency values are 0.003 and 0.004%, respectively [11]. Carbon thin film solar cells have been successfully fabricated using microwave surface wave plasma CVD with acetylene as carbon a source, trimethyl-boron as a doping source and argon as a carrier. Amorphous carbon as an intrinsic layer has an optical gap energy of 1.4 eV. Two types heterojunction solar cells with p-C/n-Si and p-C/i-C/n-Si configurations produce efficiency 0.15% and 0.51 to 2.34% respectively. The thickness of the intrinsic layer varied 35, 80 and 110 nm, respectively [12].

Amorphous carbon (*a-C*) thin films have been successfully with palm product as source using spin coating deposited on a glass ITO substrate. PES test results show that the sp^2 hybridization value is above 60% and the percentage can be adjusted by changing the heating temperature. The test results using a four-point probe showed the electrical conductivity value 2.67-8.33 S/m and electronic gap energy 0.15 - 0.49 eV. XRD test results show thar the *a-C* film is in the amorphous phase, which is indicated by the presence of a widening peak at 2 theta ~ 15^o - 30^o [13-15].

In this paper, we report the effect of photovoltaic on homojunction of amorphous carbon from biomass using a simple method. Source of biomass is liquid palmyra sugar. Liquid palmyra sugar was chosen as a source of biomass because it is a product of palmyra tree which grows a lot in the northern coastal areas of Java Island, East Nusa Tenggara, Sulawesi and Madura. Palmyra sugar made from the sap produced by palmyra tree by the heating method. Each palmyra tree produces ~ 7 liters of sap per day and is produced throughout the year [16]. Deposition method uses nano-spray because of several advantages, including: low price, light weight, portable, requires very cheap electrical power and produce an even surface layer and the deposition process can be carried out easily and simple. PES testing was carried out to determine hybridization of layers, four point probe to determine electrical conductivity, UV-Vis Spectroscopy to determine optical gap energy, SEM testing to determine cross section and thickness each layers, current and voltage testing to determine the characteristic as a rectifier and photovoltaic effect on homojunction samples.

Experiment

Preparation Sample

The process of layer deposition on the substrate begins with the manufacture of powdered amorphous carbon, boron doped amorphous carbon and nitrogen doped. Carbon powder made from liquid palmyra sugar. Liquid palmyra sugar with a yellowish brown color are heating using hot plate at a temperature 100 ^{0}C, stirred with magnetic stirrer at 200 rpm for 120 minutes to reduce the water content. This process produces dark brown thick sugar. The result is heated in a furnace at a temperature 250 ^{0}C for 150 minutes so that a very light black shinny charcoal is obtained. The charcoal is washed with distilled water, filtered with a paper filter and dried in an atmosphere. Washing and filtering is done three times. The result of filtering and drying a crushed until a very fine charcoal form is obtained.

Boron doped amorphous carbon powder made by dissolving boric acid (H_3BO_3, Merk 99,5%) in distilled water, heating using hotplate at a temperature 170 ^{0}C to obtain a solution boric acid. Amorphous carbon powder was added to the solution, heated at a temperature of 300 ^{0}C to obtain a dry boron doped amorphous carbon powder. The ratio of carbon to H_3BO_3 is 1 : 0,066 mol. Nitrogen-doped amorphous carbon powder made by mixing NH_4OH solution (merk 25%). The ratio of carbon to NH_4OH is 1 : 0,066 mol. This mixture was heated using hotplate at temperature of 170 ^{0}C and stirred using magnetic stirrer at a speed of 200 rpm to obtain a dry powder.

Preparation of *a-C, a-C*:B and *a-C*:N solution was carried out by mixing each powder with distilled water and a solution of dimethyl sulfoxide (DMSO) with ratio volume of water and DMSO 1:1. The mixture was exfoliated using ultrasonic for 120 minutes. The exfoliated product was rotated using a centrifugal player at 4000 rpm for 40 minutes to obtain of solution *a-C, a-C*:B and *a-C*:N.

A thin layer of *a-C, a-C*: B and *a-C*:N was made by depositing the prepared solution on a 2x1 cm^2 glas ITO substrate. The deposition process uses a nano-sprayer with a time deposition of 10 seconds, the distance between the substrate and the nozzle is 5 cm. The deposition of each layer on substrate was made to test the characteristics of each layer before being used as a homojunction sample. Samples of amorphous carbon homojunction are made 2 forms samples. The configuration of the two junction samples are *a-C*:B/*a-C*:N and a-C:B/*a-C*/*a-C*:N which are deposited on 1 cm^2 glass ITO substrate.

Characterization of each Layer

The test result using XRD to determine the phase of *a-C, a-C*:B and *a-C*:N films deposited on ITO glass substrate indicate the formation of an amorphous phase [17]. The form of carbon can be seen from its hybridization. Amorphous carbon has mixed sp^2 and sp^3 hybridization. The carbon film hybridization test was carried out synchrotron photoemission spectroscopy *(syn. PES)*. Hybridization of amorphous carbon without doping, boron and nitrogen doping can be studied through the 1s orbital electron transition of C, B and N atoms. The deconvolution spectrum of C1s test result using *Syn. PES* of carbon film is shown in Figure 1. The results of the C1s spectrum fittings consist of sp^2(C=C), sp^3 (C-C) and C-O hybridization with the percentage of sp^2 is 69%. The spectrum C1s at *a-C*:B shows sp^2, sp^3, C-O and C-B (sp^2) hybridization, while a-C:N shows sp^2, sp^3 (C-N) and sp^2 (C-N) [17]. This result shows that all layers (*a-C, a-C*:B and *a-C:N*) are in form of amorphous.

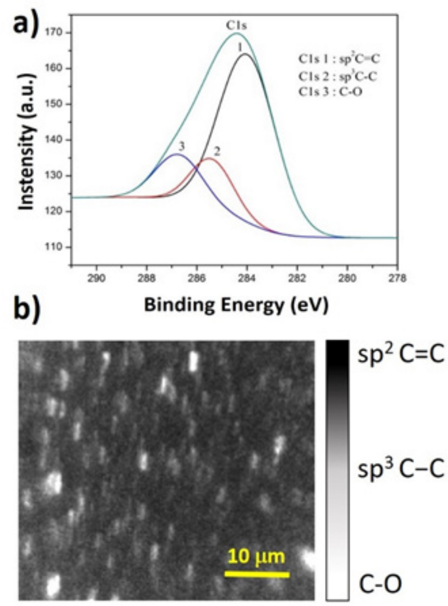

Figure 1: Spectrum C1s from *a-C* film.

The process for the formation of boron and nitrogen can be studied from the electron transition in the orbital 1s of the B and N atoms. The deconvolution spectrum of B1s is shown in Figure 2. Seen in the Figure 2 the spectrum of B1s consist 2 compounds, namely BC_3 and B_4C. Compound BC_3 shows the process of replacing carbon atom by boron. In B_4C there is no process of replacing carbon atoms by boron but defect is formed. The doping process characterized by atomic replacement. This shows that the amorphous carbon doping process with boron was formed and a positively charged *a-C*:B layer is formed and hereinafter referred to as a p-type semiconductor [19].

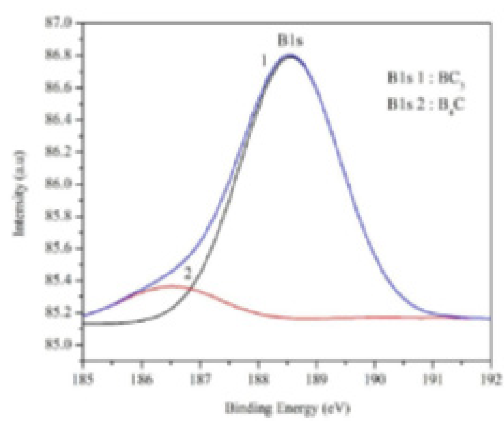

Figure 2: Deconvolution spectrum B1s.

The deconvolution results of the N1s spectrum showed that it consisted 3 compounds, namely pyridinic-N of 41.9%, pyrrolic-N of 39.56% and graphitic-N of 18.5%. Pyrrolic-N and pyridinic-N are processes of defect formation and do not affect the type of conduction, while graphitic-N is the process of replacing carbon atoms by nitrogen. The formation of graphitic-N indicates the doping process of amorphous carbon with nitrogen occurs and negative charge *a-C*:N is formed and hereinafter referred to as an n-type semiconductor [20].

Other characteristics that are indispensable in the development of solar cell materials are the energy gap and conductivity layer. The optical gap energy was measured using UV-Vis spectroscopy while electrical conductivity was measured by four point probe. Optical gap energy is determined using Tauc formula through the transmittance value while the electrical conductivity is determined from the measured current and voltage value. The value of the optical gap energy and electrical conductivity of each layer is shown in table 1. It can be seen in table 1 that the electrical conductivity values of all layers are in the category of semiconductor materials. The optical gap energy value is within the range of visible light. This allow for the formation of electron and hole pairs when the sample is irradiated with visible light.

Table 1: Conductivity and optical gap energy.

Layer	Optical gap energy (eV)	Electrical conductivity (S/m)
a-C	1.7	54.656
a-C:B	1.43	59.546
a-C:N	1.53	56.592

Junction Sample Characterization

In the photovoltaic technology, the thickness of each layer of photovoltaic cells greatly determines the performance of the cell. Optimum layer thickness is required in order to obtain maximum efficiency. The determine the thickness of each layer of the junction sample that have been made, cross-section testing is carried out using scanning electron microscope (SEM). A visual image of the cross section of the SEM test result is shown in Figure 3. As seen in Figure 3 there is a very clear of layer boundary in both samples. The thickness of each layer of the two sample is shown in table 2. Thickness of the two junction samples < 1 μm. This indicates that the junction sample is a thin layer cell. The thickness of the intrinsic layer i is smaller than that of the p and n layer.

Table 2: Sample layer thickness.

Layer	p-n junction	p-i-n junction
p (nm)	427.9	477.8
i (nm)	-	224.5
n(nm)	262.6	311.8
Cell thickness	590.5 nm	992.5 nm

The junction of two of types semiconductor with different conduction types is diode. A diode that changes in current and voltage value when irradiated with visible light is called photodiode. There is an increase in the value of current and voltage when the diode is in bright condition compared to dark condition. Seeing this, a test was carried out using a diode test circuit when it was dark and the diode was irradiated with a 1660 lux lamp. The test result are shown in table 3. It can be seen in table 3 that there is an increase in current and voltage in both sample. Sample p-i-n junction provide a higher current and voltage increase than p-n junction. This shows thar both samples have photovoltaic characteristics with p-i-n junction being more efficient than p-n.

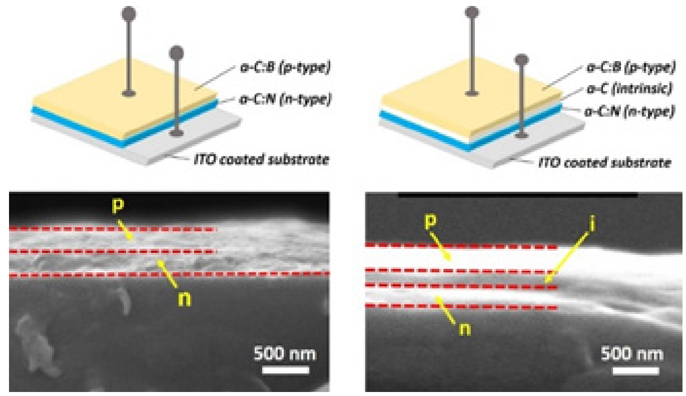

Figure 3: Cross section junction sample.

Table 3: Current and voltage in dark and light condition.

Sample	Condition	Current (nA)	Voltage (volt)
p-n	dark	122	0.11
	light	753	0.75
p-i-n	dark	128	0.13
	light	870	0.87

A diode has a curve of the relationship between current and voltage with certain shape that shows the diode is a rectifier. The test results using a diode test circuit on the p-n junction sample obtained current and voltage relationship as shown in Figure 4. Figure 4 shows that a sample p-n junction shows functioning is rectifier diode. This shows that the boron doped amorphous carbon doping process succeeded in forming p-type semiconductor and nitrogen doped succeeded in forming n-type semiconductor. As a diode, this p-n junction has a reverse current of specification of -127.7 nA, a cut in voltage of 3.6 mV and a breakdown voltage of -4.1 mV.

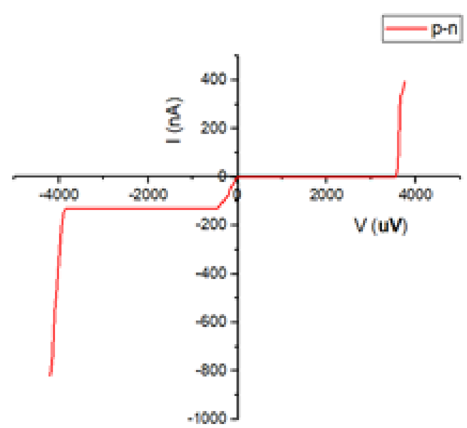

Figure 4: Curve i-v sample p-n junction.

The test results of the junction samples in bright condition showed an increase in current and voltage, giving the possibility that the two junction sample showed the photovoltaic effect and functioned as solar cells. To prove this, a current and voltage test was carried out when the sample was irradiated with direct sunlight under AM 1.5 conditions. The results of testing the current and voltage measured on the p-n junction sample obtained current and voltage relationship as shown in Figure 5. Shown in Figure 5 the relationship between current and voltage shows a curve that meets the rules of photovoltaic effect.

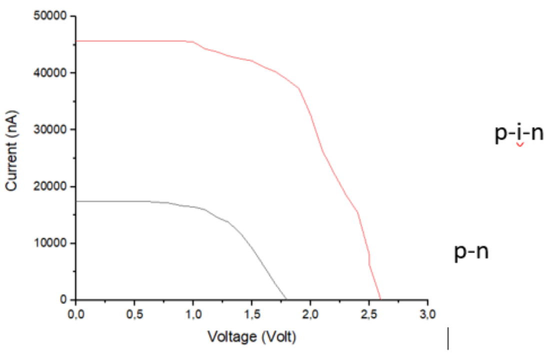

Figure 5: Curve i-v sample junction p-n and p-i-n.

The emergence of the photovoltaic effect in p-n junction indicates that when the p layer receives light, electron in the valence band get enough energy to move the conduction band become free electron. Excess hole in the p-type but cannot diffuse to the n-type because built in field in the depletion region. This causes the holes to flow toward the load resistance as drift current. Electron to the n-type pass through the built in field. In the type n electron s from valence band move to the conduction band to become free electron and leave hole in the valence band. Holes to the type-n pass through depletion region, while electrons flow to toward s the load resistance. The product of the current flowing through the load resistance and the voltage measured on the sample is the output power of the solar cell sample [20].

The current and voltage relationship in the p-i-n junction sample is shown in Figure 5. in the Figure 5 shows the relationship between current and voltage forming a curve that meets the rules for the emergence of the photovoltaic effect. The photovoltaic characteristics of two junction sample are shown in table 4. It can be seen the efficiency of the p-i-n sample is higher than of p-n sample.

Table 4: Characteristics photovoltaic sample.

Characteristics photovoltaic	p-n junction	p-i-n junction
I_{SC} (nA)	17414	45697
V_{OC} (V)	1.8	2.6
I_{Max} (nA)	15946	37305
V_{max} (V)	1.1	1.9
Fill factor (%)	55.959	59.65
Output power (mw/cm^2)	0.0175	0.0708
Efficiency (%)	0.0175	0.0708

This shows that the intrinsic layer i between layer p and n works well as an absorbent. Layer i function to increase efficiency reducing the occurrence of electron and hole pair recombination processes. The recombination process occurs due the defect in the p layer and n layer. The thickness of the absorbent layer i greatly determines the efficiency of the sample. The thickness of the absorbent layer should be chosen in such a way that maximum efficiency is obtained [21]. From the test of characteristics photovoltaic, the two junction sample can be said to be solar cell homojunction.

Table 5: Carbon solar cell efficiency value.

Researcher	Configuration	Method	Precursor	Efficiency (%)
A.N. Fadzilah [7]	Au/n-C:N/p-Si/Au	AACVD	Camphor oil	0.0002-0,0001
	a-C/p-Si			0.000048
A.N. Fadzilah [8]	Au/p-C/n-Si/Au	AACVD	Camphor oil	0.008, 0.005 & 0.003
R.U.A. Khan [9]	*p-Pa*C/(i)*a*-Si:H/ *a*-Si:H(n)	PECVD		3.84
Tetsuo Soga [10]	*a*-C/n-Si	Remote plasma cracking CVD	Fullerene [C_{60}]	0.003
	a-C/n-Si-HNO_3			0.004
Tong X. Cui [11]	Al/C_{60}/*a*-C/ITO (450^0)	CVD	CH_3CN	0.02
	Al/C_{60}/*a*-C/ITO (500^0)			0.008
S. Adhikari [12]	p-C/n-Si	SWPCVD	Acetylene	0.16
	p-C/i-C/n-Si			2.349
This research	***a*-C:B/*a*-C:N/ ITO**	**Nano-spraying**	**Palmyra sugar**	**0.0175**
	***a*-C:B/*a*-C/*a*-C:N/ITO**			**0.0708**

The value of the output power efficiency of the homojunction sample in this research is compared with the results achieved by previous researchers is shown in table 5. The table 5 shows that the efficiency of the solar cell sample with the p-i-n configuration results from this research shows a value that is comparable to what has been done by Tetsuo Soga et al., and Tong X. Cui et al. This give hope that amorphous carbon homojunction solar cells from biomass can be further developed to increase their efficiency value. The deposition method in this research uses nano-spraying which has never been used by other researcher. Nano-sprayer which is very cheap and easy to use gives hope that solar cell technology can be developed easily and at very low cost. Palmyra sugar is an agricultural product produced by palmyra trees, which is a renewable and friendly material to environment. This gives hope for the development of solar cell technology with renewable materials.

Conclusion

Sample p-n dan p-i-n junction were successfully made using simple and low cost method, with the main ingredient being the renewable palmyra sugar. Samples show an increase in current and voltage when in bright condition. The relationship between current and voltage on the p-n junction shows the characteristic of a rectifier. Current and voltage test results show that the samples function as solar cell. Based on the configuration of the sample junction and the semiconductor material used, the sample is an amorphous carbon homojunction solar cell. Based on deposition method and the main source of carbon can be said to be green solar cell.

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