FABRICATION AND USE OF Cu/Cu_2O STRUCTURE AS DIODE FOR HALF AND FULL WAVE RECTIFICATION OF AC SIGNAL

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A DISSERTATION SUBMITTED TO THE DEPARTMENT OF PHYSICS, BAYERO UNIVERSITY, KANO, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTERS IN ELECTRONICS

MAY, 2016

DECLARATION

I hereby declare that this work is the product of my research efforts undertaken under the supervision of Prof. A. O. Musa and has not been presented anywhere for the award of a degree or certificated. All sources have been dully acknowledged.

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CERTIFICATION

This is to certify that the research work for this dissertation and the subsequent write-up by *Salihu Ahmed Tijjani Mustapha (SPS/12/MPY/00006)* was carried out under my supervision.

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APPROVAL

This dissertation has been examined and approved for the award of the degree of Masters in Electronics.

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ACKNOWLEDGEMENT

Praise be to Almighty Allah, the One, the Irresistible, the Exalted, and the Forgiver of all sins. Praise belongs to Almighty Allah, the One Who makes the day turn onto night that those who have hearts take warning.

I wish to express my profound and warm gratitude to the entire member of my family. Special thanks are to my supervisor, Prof. A. O. Musa.

My sincere appreciation goes to both academic and non academic staff of physics department especially the Head of Department, Dr. T. H. Darma, and Prof. G. Babaji among others.

Lastly, I wish to express my gratitude to my friends and those who contribute towards the completion of this work.

DEDICATION

Dedicated to my late brother Engr. Ibrahim Mustapha.

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ABSTRACT

In this work Cu/Cu_2O diodes were fabricated and utilized for half and full wave rectification of an AC signal. Copper foil samples were oxidized at constant temperature of 950^o with variation in time between 3 to 5 minutes. The oxidized samples were annealed at 500^oC to form CuO|Cu_2O|Cu|Cu_2O|CuO structure. The CuO layer was removed by chemical etching process to obtain Cu/Cu_2O. The average series resistance of the Cu/Cu_2O (R_S) was found to be 197.9k**Ω**, while the non ideal factor (A) and saturation current density (J_o) for the diodes used were obtained to be 5.16 and 3.5 X 10^{-6} Acm^{-2} respectively.

CHAPTER ONE

INTRODUCTION

1.1 GENERAL INTRODUCTION

For reasons associated with economics of generation and transmission, the electric power available is usually an alternating current (AC) supply. The supply voltage varies sinusoidally and has a frequency of 50Hz/60Hz. It is used for lighting, heating etc. But there are applications (e.g. electronic circuits) where direct current (DC) supply is needed.

However, most of the electronic devices and circuits require a DC source for their operation. Dry cells and batteries are one form of dc source. They have the advantage of being portable. Their voltages are low; they need frequent replacement and are expensive as compared to conventional DC power supplies. Since the most convenient and economical source of power is the domestic AC supply, it is advantageous to convert this alternating voltage (usually, 220V) to DC voltage (usually smaller in value). When such a DC supply is required, the main AC supply had to be rectified. The main candidate chosen for this purpose is semiconductor diode.

Most solid state devices are obtained from semiconductors. As the name implies, a semiconductor material has poor conductivity (more resistance to current flow) compared to conductor but better conductivity than an insulator. A semiconductor diode on the other hand, is created by simply bringing together an n-type and p-type material, nothing more; just the joining of one material with a majority carrier of electrons to one with a majority carrier of holes (Boylestad and Nashelsky, 2012).

Copper (I) oxide or cuprous oxide is an inorganic compound with the formula Cu_2O. It is one of the principal oxides of copper. This red-coloured solid is a component of some antifouling paint. The compound can appear either yellow or red, depending on the size of the particles. Copper (I) oxide is found as the reddish mineral cuprites. Copper (I) oxide may be produced by several methods. Most straightforwardly, it arises via the oxidation of copper metal.

Rectifier diodes based on this material such as Cu/Cu_2O were used industrially as early as 1924 and most of the theory of semiconductors was developed using the data on Cu_2O based devices (Biccari, 2009).

1.2 PREVIOUS WORK

The work of Onimisi (1999), was look at and it was observed that lead (Pb) was used to joined the fabricated diodes instead of silver paste that was used in this work. The thermal oxidation time was from five to seven minutes and the maximum number of fabricated diodes joined together was four. The diode non-ideal factor (A) and the dark saturation current density (J_o) were respectively 64.33 and 0.12×10^{-8} Acm^{-2}

In this work the thermal oxidation time was from three to five minutes and the maximum number of fabricated diodes joined together was three. The diode non ideal factor (A) and the dark saturation current density (J_o) were respectively recorded as 5.16 and 3.5×10^{-6} Acm^{-2}.

1.3 STATEMENT OF THE PROBLEM

There is the need to fabricate some electronic devices which are very central to the functioning of many of our household appliances. One of these devices is the diode. The possibility of fabricating metal-semiconductor diodes (Cu/Cu_2O) for rectification is proposed in this work using pure copper foils (99.98% purity) by the process of partial thermal oxidation. It is envisaged that this will in future bring down the cost of these devices if it can be indigenously fabricated.

1.4 AIM AND OBJECTIVES

The aim of this research work is to fabricate metal-semiconductor diodes (Cu/Cu_2O) using partial thermal oxidation of copper foil. The objectives of the study are to:

i. prepare copper (l) oxide (Cu_2O) as a starting material for a diode by partial thermal oxidation of copper foil (Cu),
ii. study the current – voltage characteristics of the diodes,
iii. determine the series resistance R_s, the diode non- ideal factor A, and the dark saturation current density J_o of the diode,
iv. study the rectifying properties of the diodes,
v. use the fabricated diodes to test for half and full wave rectification of AC signal.

1.5 MOTIVATION

Cu_2O diode was chosen for this study because it is considered as an attractive material for fabrication of metal-semiconductor diodes due to its easy availability, non-toxicity and relatively low cost of its constituents. Moreover, the fabrication of Cu/Cu_2O diodes was considered in this study due to high demands of diodes in the market.

1.6 SCOPE AND LIMITATION

The scope of this study is to fabricate metal semiconductor diodes (Cu/Cu_2O) by preparing copper (I) oxide (Cu_2O) as a starting material for a diode by partial thermal oxidation of copper foil (Cu), to study the current voltage characteristics of the fabricated diodes using I-V- characteristics measurement circuit, to determine the series resistance R_s, the diode non ideal factor A, and the dark saturation current density J_o of the diode from the I-V characteristics curve and to use the fabricated diodes to test for half and full wave rectification of AC signal using the half and full wave rectification circuit.

The study was limited to thermal oxidation time of three to five minutes, annealing time of one hour and one and half hour and the maximum number of fabricated diodes joined together was three. It was also limited to test for half and full wave rectification of AC signal.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

The previous works of many researchers have been look at. Based on this, it was discovered that Cu_2O had been one of the earliest semiconductors and one of the most studied materials. Many experimental observations and semiconductor applications have been demonstrated first in this material. Apart from its attractiveness as a starting material for use as solar cell for low cost terrestrial conversion of solar energy to electricity, it also serves as a good starting material for metal-semiconductor diodes. It is said to be one of the earliest known photovoltaic material and hence a diode material and the first in which the photovoltaic effect was successfully explained (Furtine and Sears, 1981).

However, although earliest research shows that the performances of Cu_2O diodes are poor relative to that of the developed silicon and germanium diodes, it is still considered as an attractive material for fabrication of metal-semiconductor diodes due to its easy availability, non-toxicity and relatively low cost of its constituents.

2.2 HISTORICAL PERSPECTIVE

In the history of semiconductor physics, Cu_2O is one of the earliest semiconductors (Musa, 2010). It is also one of the most studied materials, and many experimental observations and semiconductor applications have been demonstrated first in this material. Rectifier diodes based on this material (such as Cu/Cu_2O) were used industrially as early as 1924, long before silicon became the standard and most of the theories of semiconductors was developed using the data on Cu_2O based devices.

The name “cuprite” of cuprous oxide Cu_2O comes from the Latin “cuprum”, meaning copper (Korzhavyi and Johansson, 2011). Old miners used to call it “ruby copper”. Cuprite mineral has been a major ore of copper and is still mined in many places around the world. Korzhavyi and Johasson (2011) observed that of all the copper ores, except for native copper, cuprite gives the greatest yield of copper per molecule since there is only one oxygen atom to every two copper atoms. As a mineral specimen, cuprite shows fine examples of well-developed cubic crystal forms. Crystal habits include the cube, octahedron, dodecahedron, and combinations of these forms. Cuprite’s colour is red to a deep red that can appear almost black. Dark crystals show internal reflections of the true deep red inside the almost black crystal. Other varieties, such as chalcotrichite, form long needle-like crystals that have a beautiful red color and a special sparkle that make them popular display cabinet specimens.

Cuprite (or cuprous oxide) is the oldest material of semiconductor electronics (Brattain 1951). It has been the subject of numerous theoretical and experimental studies, but still its electronic and atomic structures continue to puzzle the researchers. New applications of Cu_2O in nanoelectronics, spintronics, and photovoltaics are emerging. However, the present interest in this material is motivated by the fact that Cu_2O is a commonly occurring corrosion product of copper. Understanding cuprite at the electronic and atomic structure levels may be useful for predicting and controlling the corrosion behavior of copper.

2.3 THEORETICAL CONSIDERATIONS

When a crystal of compound XY is formed it is usually thought of as having equal numbers of X and Y atoms. Such a crystal is said to be stoichiometric. However, this stoichiometry is not obeyed by many solids as the ratio of atoms in them is slightly different from the ratio in one mole. Such non-stoichiometric compounds balance their structures by the presence of defects: vacancies, interstitials or both (Sear and Fortin, 1984). Cuprous oxide is one of such non-stoichiometric materials with formula $Cu_{2-\delta}O$. The deviation from stoichiometry, δ is generally attributed to some imperfections. Sear and Fortin reported that an excess of oxygen, as a result of stoichiometry, is the major active impurity and gives a p-doped semiconductor.

2.3.1 P-N Junction

When a junction is formed of n-type and p-type materials (fig. 2.1), some of free electrons from the n-type material diffuse across the junction and combine with the holes in the p-type material.

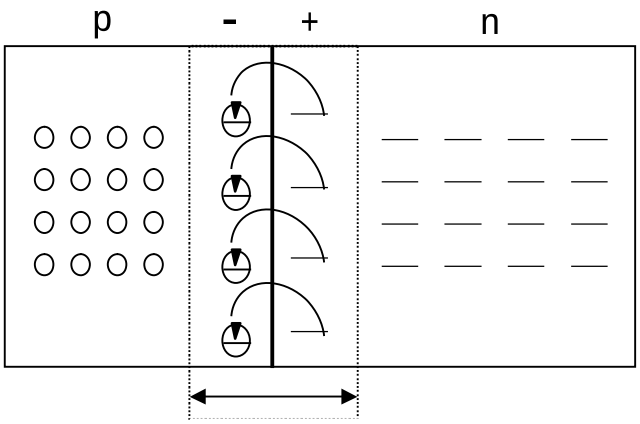

Figure 2.1. P-N junction.

The combined holes become negative because of the excess electrons and the area lacking in electron in the n-type material becomes positive. This interaction creates a small space-charge region (often called the transition region or a depletion layer) in the immediate vicinity of the junction. When an external voltage source is connected across the p-n junction, its behavior is completely different depending on the connection polarity.

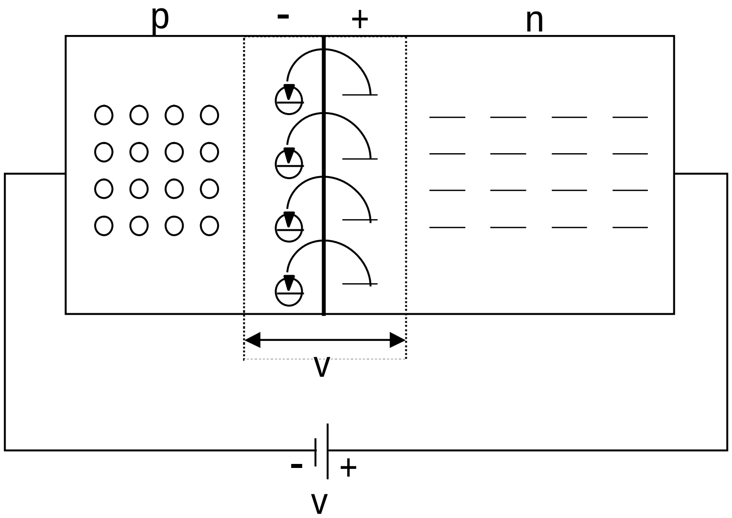

Figure 2.2. Reverse bias P-N junction.

Because of the voltage source, more electrons diffuse from the n-type material to the p-type material. The depletion layer is expanded. The space-charge region voltage becomes equal to the voltage source and current does not flow. Electrons cannot flow from the p-type material to the n-type material.

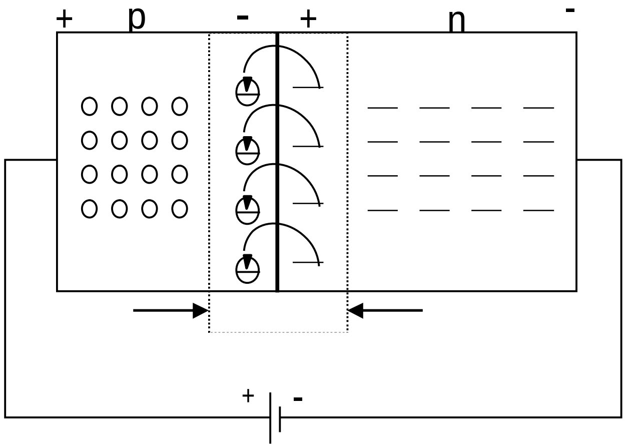

Figure 2.3. Forward bias P-N junction.

The space-charge region becomes effectively narrower. The source negative voltage pole drives electrons to the n-type material. The excess electrons diffuse to the p-type material and flow through the holes to the voltage positive source pole.

2.3.2 Semiconductor Diode

A diode is an electrical device allowing current to move through it in one direction with far greater ease than in the other. The most common kind of diode in modern circuit design is the semiconductor diode, although other diode technologies exist. The tern “diode” is customarily reserved for small signal devices, -1 ≤ 1A.

The p-n junction is a semiconductor diode. Its symbol is:

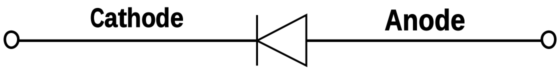

Figure 2.4. Semiconductor diode symbol.

Current can flow through the diode only in one direction from the anode to the cathode. Current flows through the diode when the cathode is negatively charged relative to the anode at a voltage greater than a certain minimum called forward break over. If the cathode is positive with respect to the anode, is at the same voltage as the anode, or is negative by an amount less than the forward break over voltage, then the diode does not conduct current. The forward break over voltage is approximately six tenths of a volt (0.6 V) for silicon devices, 0.3 V for germanium devices, and 1 V for selenium devices.

The above general rule notwithstanding, if the cathode voltage is positive relative to the anode voltage by a great enough amount, the diode will conduct current. The voltage required to produce this phenomenon, known as the avalanche voltage, varies greatly depending on the nature of the semiconductor material from which the device is fabricated. The avalanche voltage can range from a few volts up to several hundred volts.

2.3.3 Current-voltage Characteristics Curve of a Diode

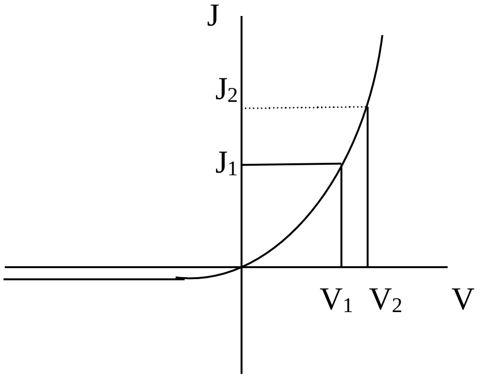

Figure 2.5. J-V characteristics curve.

For a non-ideal diode: $J = J_o\,[\exp(\frac{qv}{AKT}) - 1]$ -------------------- (2.1)

where $J = \frac{I}{Area}$, J is the current density, J_o is the saturation current density, q is the charge density, v is the voltage, k is the Boltzmann constant, A is the non-ideal factor of the diode and T is the temperature.

2.3.4 Evaluation of J_o and A for a Diode

In forward bias, $\exp(\frac{qv}{AKT}) \gg 1$,

Therefore equation (2.1) becomes; $J \approx J_o \exp(\frac{qv}{AKT})$ -------------------- (2.2)

At a temperature T= 300K, the quantity $\frac{qV}{kT}$ is

$\frac{qV}{kT} \approx 38.7V^{-1}$ -------------------- (2.3)

(where $q = 1.602 \times 10^{-19}$ C and Boltzmann's constant $k = 1.380\times10^{-23}$ J/K)

From fig.2.5,

$$J_1 = J_o \exp\left(\frac{q V_1}{AkT}\right) \qquad \text{-------------------- (2.4)}$$

$$J_2 = J_o \exp\left(\frac{q V_2}{AkT}\right) \qquad \text{-------------------- (2.5)}$$

So that

$$\frac{J_2}{J_1} = \exp\left[\frac{q}{AkT}(V_2 - V_1)\right] \qquad \text{-------------------- (2.6)}$$

$$In\left(\frac{J_2}{J_1}\right) = \frac{q}{AkT}(V_2 - V_1) \qquad \text{-------------------- (2.7)}$$

$$AkTIn\left(\frac{J_2}{J_1}\right) = (V_2 - V_1) \qquad \text{-------------------- (2.8)}$$

$$A = \frac{q}{kT}\left[\frac{V_2 - V_1}{In\left(\frac{J_2}{J_1}\right)}\right] \qquad \text{-------------------- (2.9)}$$

$$A = 38.7\left[\frac{V_2 - V_1}{In\left(\frac{J_2}{J_1}\right)}\right] \qquad \text{------------------- (2.10)}$$

2.3.5 The Diode Under Bias

When forward bias voltage is applied to a diode, the diode conducts and acts as a very low resistor. The forward voltage drop on the diode remains substantially constant as long as the average current is within the rated value of the rectifier. Over the rated value the rectifier may be damaged.

2.3.6 Zener Diode

The zener diode is the basic component in regulation circuits. The zener diode is a diode aimed to operate in its reverse breakdown voltage. There are many zener diodes with various breakdown voltages.

The regulator's purpose is to supply a fixed direct voltage, which does not depend on changes in its input voltage or in the current consumption.

The important regulator parameters are:

The regulation load current coefficient, which is called, output resistance:

$$R_o = \frac{\Delta V_o}{\Delta I_L} \qquad \text{-------------------} \ (2.11)$$

The regulation input voltage coefficient:

$$S_V = \frac{\Delta V_o}{\Delta V_i} \qquad \text{-------------------} \ (2.12)$$

Every regulator has a minimum input voltage, which is necessary to maintain the required output voltage.

The zener breakdown voltage is called V_Z. The zener diode symbol is:

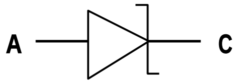

Figure 2.6. Zener diode symbol.

The zener characteristic is as follows:

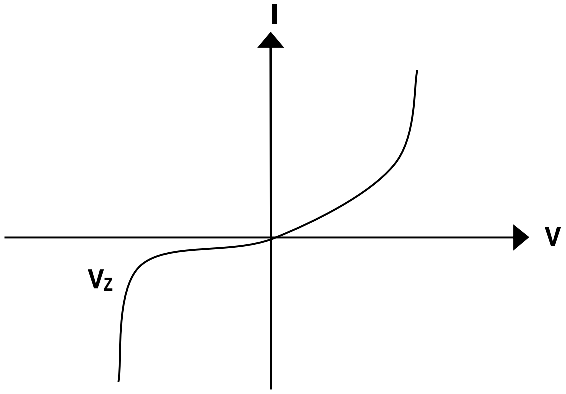

Figure 2.7. Zener characteristic.

In forward bias, the zener diode acts as an ordinary diode.

In reverse bias voltage over the zener voltage, the diode break down and changes in its current almost do not affect the zener voltage.

The gradient of the zener area line determines the zener dynamic resistance R_d.

The following circuit is a zener regulation circuit;

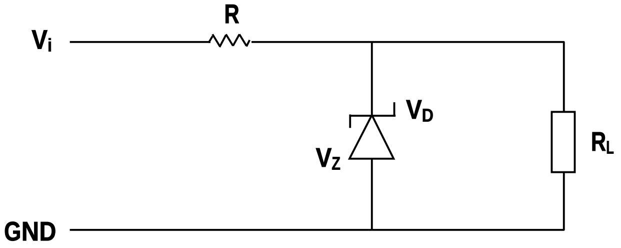

Figure 2.8. Zener regulation circuit.

Assuming $V_i > V_Z$ and also $V_{RL} > V_Z$ (if there is no zener diode) then $V_D = V_Z$. The R accepts the voltage difference between V_i and V_Z. Even if V_i changes, the voltage on R_L is fixed and equal to V_Z.

Every zener diode has the maximum power dissipation rating. This rating determines the zener maximum current. We try to operate the zener in 10-20% of this maximum current. In this way, the diode will be in the linear part of the breakdown range and with a lower power than the maximum power rating.

2.3.7 Current Transport Theory in Schottky Barriers

Another type of junction diode, the Schottky diode, is formed from a metal-semiconductor junction rather than a p–n junction, which reduces capacitance and increases switching speed. The current transport in Schottky barriers is mainly due to majority carriers. Schottky in 1938 proposed the isothermal diffusion theory, whereas Bette in 1942 proposed a simple isothermal emission model (Sze, 1985). However, in 1966 Crowel and Sze synthesized the two models into a single, more generalized theory with a current-voltage relation as:

$I = qN_C\mu E\exp\left(\frac{-q\phi_B}{KT}\right)\left[\exp\left(\frac{qV}{AKT}\right)^{-1}\right]$ ------------------- (2.13)

or $I = I_S\left[\exp\left(\frac{qV}{AKT}\right)^{-1}\right]$ ------------------- (2.14) where $I_S = qN_C\mu E\exp\left(\frac{-q\phi_B}{KT}\right)$ = dark saturation current

N_C = effective density of states in the conduction band

μ = mobility of electrons

E = junction electric field

ϕ_B = metal –semiconductor barrier height.

2.4 HALF-WAVE RECTIFICATION

A device, such as the semiconductor diode, which is capable of converting a sinusoidal input waveform (whose average value is zero) into a unidirectional (though not constant) waveform, with a non-zero average component, is called a rectifier. Since in a rectifier circuit fig 2.9a, the input $V_i = V_m\sin\omega t$ has a peak value V_m which is very large compared with the cut-in voltage V_y of the diode. With the diode idealized to be a resistance R_f in the ON state and an open circuit in the OFF state, the current i in the diode or load R_L is given by

$$\left.\begin{aligned} i &= I_m sin\alpha && \text{if } 0 \le \alpha \le \pi \\ i &= 0 && \text{if } \pi \le \alpha \le 2\pi \end{aligned}\right\} \qquad \text{-------------------} (2.15)$$

Where $\alpha = \omega t$ and $\omega = 2\pi f$, f is the frequency and t is the time.

$$I_m \equiv \frac{V_m}{R_f + R_L} \qquad \text{-------------------} (2.16)$$

Where R_f is the forward resistance, R_L is the load resistance, I_m is the peak load current, V_m is the peak voltage and i is the current.

The transformer secondary voltage V_i (Fig. 2.9b), and the rectified current (Fig. 2.9c). We now calculate this non-zero value of the average current.

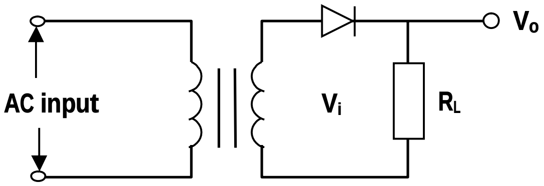

Figure 2.9a. Basic circuit of Half wave rectifier.

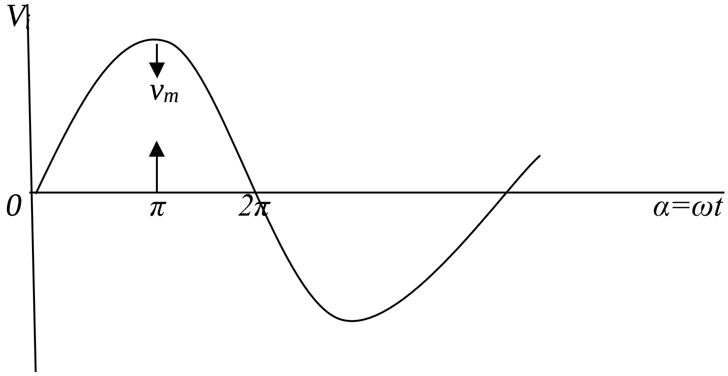

Figure 2.9b. Transformer sinusoidal secondary voltage.

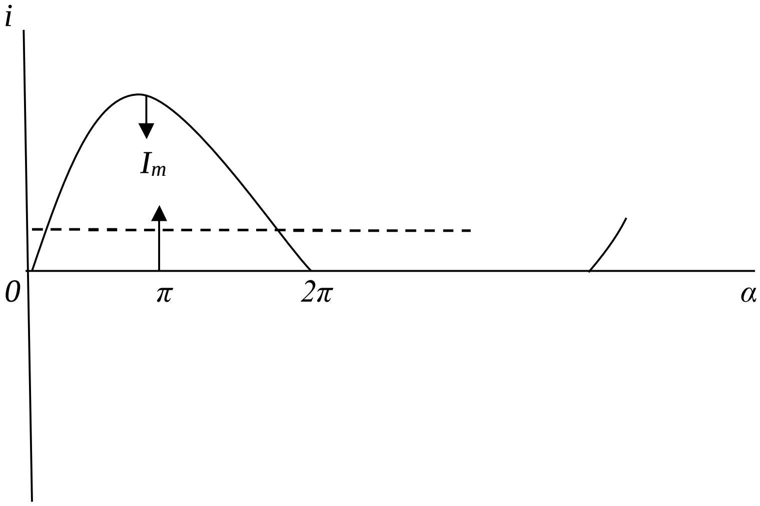

Figure 2.9c. Diode and load current *i*.

A root mean square ammeter (voltmeter) is designed so that its reading indicates the effective, or, rms, current (voltage). By definition, the effective or rms value squared of a periodic function of time is given by the area of one cycle of the curve, which represents the square of the function, divided by the base. Expressed mathematically,

$$I_{rms} = \left(\frac{1}{2\pi}\int_0^{\pi} i^2\, d\alpha\right)^{½} \qquad \text{------------------- (2.17)}$$

By use of eq. (2.15), it follows that

$$I_{rms} = \left(\frac{1}{2\pi}\int_0^{\pi} i^2 \sin^2\alpha\, d\alpha\right)^{½} = \frac{I_m}{2} \qquad \text{------------------- (2.18)}$$

Applying eq. (2.17) to the sinusoidal input voltage, yields

$$V_{rms} = \frac{V_m}{\sqrt{2}} \qquad \text{------------------- (2.19)}$$

2.5 FULL-WAVE RECTIFICATION

The circuit of a full wave rectifier (Fig. 2.10a), is seen to comprise two half wave circuits so connected that conduction takes place through one diode during one half of the power cycle and through the other diode during the second half of the cycle.

The current to the load, is the sum of these two currents (Fig. 2.10b). The dc and rms values of the load current and voltage in such a system are readily found to be

$$\left.\begin{aligned} I_{dc} &= \frac{2\,I_m}{\pi} \\ I_{rms} &= \frac{I_m}{\sqrt{2}} \\ V_{dc} &= \frac{2 I_m R_L}{\pi} \end{aligned}\right\} \qquad \text{------------------- (2.20)}$$

$$V_{dc} = \frac{2\,V_m}{\pi} - I_{dc}\, R_f \qquad \text{------------------- (2.21)}$$

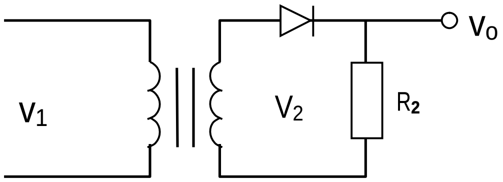

Figure 2.10a. Full wave rectifier circuit.

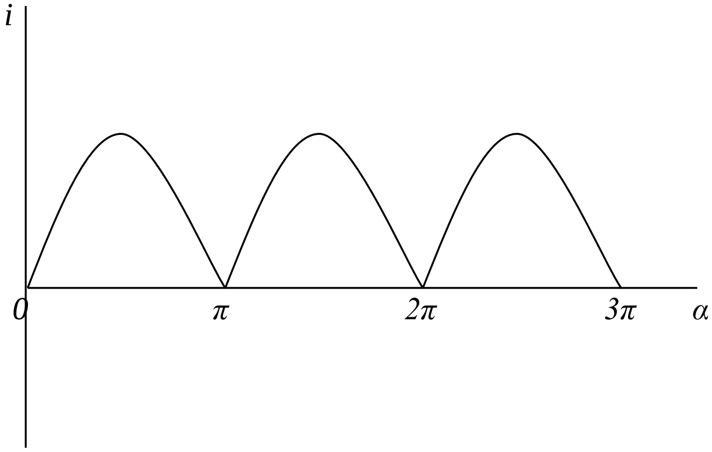

Figure 2.10b. Full wave rectifier waveform.

2.6 METHODS OF PREPARATION OF Cu_2O

According to Samarasekara (2010), copper forms two different oxides such as cuprous oxide (Cu_2O) and cupric oxide (CuO). Samarasekara (2010) continued that Cu_2O is a p-type semiconductor and has a band gap of 2.1 eV. CuO is an n-type semiconductor with band gap of 1.21 - 1.51 eV. Cu_2O is a brown yellowish material and CuO is a black colour material. It is known that CuO is more thermally stable materials and thus oxidation of Cu_2O produces CuO. Both Cu_2O and CuO have been investigated for gas sensor applications, catalysts as well as photocells. CuO is a low coast material. Thin films of CuO have been prepared using spray pyrolysis and electrochemical methods. Thin films of Cu_2O have been fabricated using the reactive sputtering methods, molecular beam epitaxy, chemical vapor deposition and reactive rf (radio frequency) magnetron sputtering. The CuO is typically prepared by chemical methods and high temperature oxidation of copper. It is easy to form CuO than Cu_2O because of the stability of CuO with high oxidation number.

Synthetic crystals of Cu_2O have been prepared in several ways, mainly by partial thermal oxidation of copper in furnace, by electro-deposition and by sputtering (Abdu and Musa, 2009).

High purify copper foil can be polished using sandpapers. Which can be latter be cut into standard size wafers of 2cm by 4cm (*Musa et al.*, 1998), 5cm by 3cm etc. depending on the required size. The samples can be thoroughly washed in acetone nitric acid solution then repeatedly rinsed in deionized water or distilled water. Latter be removed and dried with tissue paper in a dust free air environment.

The simplest way to obtained Cu_2O consists in oxidizing a copper sheet in an atmosphere containing oxygen (Biccari, 2009). Biccari (2009) continued that the chosen temperature and oxygen partial pressure of the oxidation must be in the region of stability of Cu_2O. Experimentally it was found that copper, like almost all metals, oxidizes in the presence of oxygen gas in the form of a uniform film of oxide which, except for very thin films, if the temperature and oxygen partial pressure are constant, increases in thickness proportionally with the square root of the time (parabolic rate constant), suggesting an underlying diffusion process.

The oxidation can be carried out at atmospheric pressure in a high-temperature tube furnace (*Musa et al*., 1998). A ceramic crucible can be used to hold the samples. When the oxidation temperature was reached, the samples can be placed inside the furnace. The temperature and time of oxidation can be varied for both complete and partial oxidation of the samples. *Musa et al*. (1998) continued that some specimens were oxidized in the presence of HCl vapour. A flow of Ar gas at a pressure of 5 X 10^{-4} Nm^{-2} from a high-pressure cylinder transports the HCI vapour to the samples during oxidation. After the oxidation, the samples can be rapidly quenched in distilled water. The furnace temperature can be reduced to 500°C and the samples can be given a second heat treatment (annealing) for 90 min, and followed by a second quenching. Black CuO was always formed on the surface of the Cu_2O after the quenching process and for all oxidations carried out below 1040°C. Selective etching to remove CuO can be performed using a solution consisting of FeCl, HCl, and 8M HNO containing NaCl. The last stage of the etching process can be carried out in a solution of ammonium persulphate in water.

According to Georgieva and Ristov (2002), the oxidation can be carried out in a high temperature furnace. The oxidation temperatures can be chosen from 950^{o}C to 1050^{o}C. A ceramic crucible can be used to hold the samples which were placed inside the furnace at the preset reached temperature. These can be oxidized for various length of time so as to determine the optimum time of oxidation. The lengths of the oxidation time can be varied after which the best of the samples can be selected. When the oxidation time was attained, the oxidation process can be stopped by quenching the oxidized samples in cold distilled water. This can be allowed to dry in a dust free air. The samples will turn black which indicate the presence of copper (ll) oxide (CuO) on top of copper (l) oxide (Cu_2O). The reaction was;

$$4Cu + O_2 \rightarrow 2Cu_2O \qquad \text{----------------} \ (2.22)$$

$$Cu_2O \rightarrow CuO + Cu \qquad \text{----------------} \ (2.23)$$

The CuO can be removed using an etching solution containing $FeCl_2$, HCl and NaCl in distilled water.

Georgieva and Ristov (2002) continued that a very simple apparatus can be used for electro-deposition. It consisted of a thermostat, a glass with solution, two electrodes (cathode and anode) and a standard electrical circuit for electrolysis. A copper clad for printed circuit board, with dimension 50mm, 2.5 X 7cm^2, can be used as the anode. Commercial conducting glass coated with ITO (Indium Tin Oxide), deposited by the use of the spraying technique, can be used as a cathode. Experience shows that impurities (such as dirt, finger prints, etc.) on the starting surface material have a significant impact on the quality of the solar cells. Therefore, mechanical and chemical cleaning of the ITO substrates, prior to the cell preparation, is essential. Copper boards can be polished with fine emery paper and dipped in hydrochloric acid. They can be washed by liquid detergent and distilled water. The ITO substrates can be cleaned with liquid detergent and then dipped into a solution of sodium hydroxide for a period of one hour and rinsed with distilled water. The deposition solution contained 64g/l anhydrous cupric sulphate ($CuSO_4$), 200ml/l lactic acid ($C_3H_6O_3$) and about 125g/l sodium hydroxide (NaOH). Cupric sulphate was dissolved first in distilled water giving it a light blue color. Lactic acid can then be added. Finally, a sodium hydroxide solution can be added, changing the color of the solution to dark blue with pH=9. Thin films of Cu_2O were electrodeposited by the cathodic reduction method of an alkaline cupric lactate solution at 601C on glass coated with ITO. The deposition can be carried out under constant current density. The best ITO/Cu_2O solar cell was obtained under the following conditions: current density j¼ 0:57mA/cm^2, voltage between the electrodes V¼ 1:121:05V and deposition time t¼ 135min. From the value of current density, deposition time and Faraday’s law, the Cu_2O

oxide layer thickness was estimated to be 5.8mm. All the deposited films had reddish to reddish-gray color.

The properties of the electrodeposited films of Cu_2O are largely similar to those prepared by thermal oxidation. The grain sizes of the electro-deposits vary from 0.1 to 10µm.The major problem, however, is in the high resistivity (104 – 106 ohmcm) of the electro-deposited Cu_2O film.

Cathode sputtering is essentially one of the methods used for the preparation of thin films. The method requires very low pressure in the working space and therefore makes use of vacuum technique. The material to be sputtered is used as a cathode in the system in which a glow discharge is established in an inert gas at a pressure of 10-1 – 10-2 torr and a voltage of a few kilovolts. The substance on which the film is to be deposited is placed on the anode of the system. The positive ions of the gas created by the discharge are accelerated towards the cathode (target). Under the bombardment of the ions the material is removed from the cathode (mostly in the form of neutral atoms or in the form of ions). The liberated components condense on surrounding areas and consequently on the substrates placed on the anode. Reactive sputtering is used in the production of Cu_2O. A chemical reaction that occurs with the cathode material (Cu in this case) by the active gas (oxygen) either added to the working gas or as the working gas itself. The resistivity of the deposited Cu_2O film can be controlled over a wide range by simply varying the oxygen pressure. Cu_2O films of resistivity as low as 25 ohmcm have been reproducibly obtained by this technique.

The best of oxidized samples can be selected for the annealing process. The process can be carried out in a high temperature furnace. The annealing temperature can be preset to 500°C. When the oxidation temperature is reached, the samples can be inserted inside the furnace. The annealing time can be varied from one hour to one hour thirty minutes. When the annealing time is reached, the samples can be removed from the furnace and quenched in distilled water.

After annealing, the best of the annealed samples can be selected. The CuO layer can be removed by chemical etching process. For this process, $FeCl_2$ and NaCl were dissolved in cold distilled water. Concentrated HCl was added to the solution. The samples can then be dipped into this solution and gently shaken for about two minutes until the reddish brown colour of Cu_2O were obtained. After the first etching process, the black CuO layer can be removed so that the structure left will be of the form:

$$|Cu_2O|Cu|Cu_2O|$$

Cu_2O was removed from one surface to obtain Cu/Cu_2O structure.

2.7 FABRICATION OF Cu_2O RECTIFIERS

According to Onimisi (1999), Cu_2O rectifiers can be fabricated by evaporating metal films onto polycrystalline Cu_2O waters which had been etched for ten seconds with $8MHHO_3$. Shocttky barrier studied have involved device fabricated with metal characterized by a large range of work functions. It was observed that all the contacts except the Au/Cu_2O contact exhibit properties similar to Cu/Cu_2O rectifiers. A Schottky barrier Cu_2O rectifier is usually fabricated by evaporating a metal on top of Cu_2O in high vacuum chambers. This can also be carried out by the procedures developed for Schottky barriers on thermally oxidized Cu_2O discussed above. Schottky barrier rectifier can also be fabricated in the back-wall structure. This method involved a natural junction using copper or any other material as base and depositing a layer of Cu_2O on top of the metal base. Under darkness, typical diodes were reported to offer an infinite resistance when voltage of one polarity is applied, but a zero resistance voltage of opposite polarity is applied.

2.8 APPLICATIONS OF SEMICONDUCTOR DIODES

One significant application of diodes is to convert ac power to dc power. A single diode or four diodes can be used to transform 110V household power to dc by forming a half-way (single diodes) or a full-wave (four diodes) rectifier. A diode does this by allowing only half of the ac wave form to travel through it. When this voltage pulse is used to charge a capacitor, the output voltage appears to be a steady dc voltage with a small voltage ripple. Using a full wave rectifier makes this process even more efficient by routing the ac pulses so both the positive and negative haves of the input sine wave are seen as only positive pulses, effectively doubling the frequency of the input pulses to the capacitor which help keep it charged and deliver a more stable voltage.

Another use for diodes is to remove the negative component of an ac signal so it can be worked with easier with electronics. Since the negative portion of an ac waveform is usually identical to the positive half, very little information is effectively lost in this process. Signal demodulation is commonly used in radios as part of the filtering system to help extract the radio signal from the carrier wave.

Diodes also function well as protection devices for sensitive electronic components. When used as voltage protection devices, the diodes are non-conducting under normal operating conditions but immediately short any high voltage spike to ground where it cannot harm an integrated circuit. Specialized diodes called transient voltage suppressors are designed specifically for over-voltage protection and can handle very large power spikes for short time periods, typical characteristics of a voltage spike or electric shock, which would normally damage components and shorten the life of an electronic product.

Another basic application of diodes is to steer current and make sure it only flows in the proper direction. One area where the current steering capability of diodes is used to good effect is in switching from a power supply to running from a battery. When a device is plugged in and charging, for example a cell phone or uninterruptible power supply, the device should be drawing power only from the external power supply and not the battery and while the device is plugged in the battery should be drawing power and recharging. As soon as the power source is removed, the battery should power the device so no interruption in noticed by the user.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1 INTRODUCTION

Research shows that Cu_2O can be obtained from copper foil by partial thermal oxidation at very high temperature. Though this is not the only method for obtaining Cu_2O, other methods like by electro-deposition and by sputtering can also be apply. Thermal oxidation is the simplest method and it was chosen for is simplicity. Experimentally it was discovered that copper, like almost all metals, oxidizes in the presence of oxygen gas in the form of a uniform film of oxide.

3.2 MATERIALS

The materials used for the experiment are; copper foil (0.1mm thickness and 99.98% purity), a very high temperature Vecstar chesterfield U.K furnace (max 1,200^{o}C), model: LF2MQD, silver paste, ceramic crucibles (that can withstand a temperature of above 1000^{o}C), oscilloscope type: PM3233, Baku BK-1502DD power supply, LY0440 analog D.C voltmeter, LY0407 analog D.C ammeter meter, germanium 1N270 diode, improvised rectification module, I-V characteristics module, distilled water, nitric acid, ferric chloride ($FeCl_2$), sodium chloride (NaCl), concentrated hydrochloric acid (HCl), a pair of scissors, a face marks, a hand gloves, a tissue paper and a long tongs.

3.3 TREATMENT OF COPPER FOIL

High purify copper foil (99.98% purity, 0.1mm thickness) was straighten using the edge of a beaker which was later be cut into a standard size wafers of 1cm by 1cm. These samples were thoroughly clean in nitric acid for five seconds. They were then removed and repeatedly rinsed in distilled water which was later dried with tissue paper in a dust free air environment.

3.4 THERMAL OXIDATION OF THE SAMPLES

The oxidation was carried out at atmospheric pressure in a high temperature furnace (max 1,200°C). The oxidation temperature was preset at 950°C. Ceramic crucibles were used to hold the samples which were placed inside the furnace when the preset temperature is reached. The samples were divided into A, B and C groups. It was oxidized for three, four and five minutes respectively so as to determine the optimum time of oxidation. After which the best of the oxidized samples were selected. The oxidized samples were quenched in cold distilled water. The samples were dried with tissue paper in a dust free air environment. The samples look black which indicate the presence of copper (ll) oxide (CuO) on top of copper (l) oxide (Cu_2O). The structure obtained was observed to be of the form:

$$CuO|Cu_2O|Cu|Cu_2O|CuO$$

The reaction was:

$$4Cu + O_2 \rightarrow 2Cu_2O \qquad \text{-------------------} \ (3.1)$$

$$2Cu_2O \rightarrow 2CuO + 2Cu \qquad \text{-------------------} \ (3.2)$$

3.5 ANNEALING OF THE SAMPLES

The annealing process was carried out using high temperature furnace at a reduced annealing temperature of 500°C. When the annealing temperature is reached, the samples were placed inside the furnace. Each of oxidized samples (i.e. A, B and C) is divided into two (i.e. samples A_1, A_2, B_1, B_2, C_1 and C_2). The annealing time was varied from one hour to one hour thirty minutes. Samples A_1, B_1 and C_1 were annealed for one hour whereas samples A_2, B_2 and C_2 for one hour thirty minutes. When the annealing time is reached, the samples were removed from the furnace, quenched in distilled water and dried with tissue paper in dust free air environment.

3.6 CHEMICAL ETCHING OF THE SAMPLES

After annealing, the CuO layer was removed using the chemical etching process. An etching solution ($FeCl_2$, HCl and 8M HNO_3 NaCl in distilled water) was used. The samples were dipped into this solution and gently shaken for about two minutes until the reddish brown colour of Cu_2O were obtained. After the first etching process, the black CuO layer was removed. The structure left was observed to be of the form:

$$|Cu_2O|Cu|Cu_2O|$$

Cu_2O layer was removed from one surface using concentrated HCl solution so that the structure left was of the form:

$$Cu/Cu_2O$$

3.7 FABRICATION OF THE Cu/Cu_2O DIODE

In order to fabricate the Cu/Cu_2O diodes, the two conducting wires, one at the positive (Cu_2O) and the other at the negative (Cu) terminal were made with the use of silver paste. This was allowed to dry for at least twelve hours to ensure good electrical contact.

In order to achieve the best results a number of these structures (of the same history) were joined together ranging from two to three. The current-voltage characteristics were measured and the rectifying properties for each case were studied for different samples.

It was observed that, the performances of the fabricated diodes were poor when only one Cu/Cu_2O structure was used. Whereas when two of these structures were used, average performances were observed. However, it was observed that when three of these structures were used, the fabricated diodes of this material have the highest performances. This shows that three Cu/Cu_2O structures are better than one and two Cu/Cu_2O structures.

3.8 CURRENT-VOLTAGE CHARACTERISTICS MEASUREMENT

After the fabrication process, the current-voltage characteristics were used to evaluate the values of the series resistance, R_S, the saturation current density, J_o and the non ideality factor, A. The values of various forward bias voltages (ranging from 0.1-0.2 V) and the corresponding values of the currents in mA were obtained using voltmeter and milli-ammeter respectively.

The terminals were reversed to obtain the negative values of the voltmeter with corresponding values of mili-ammeter used.

A graph of current against voltage was plotted for both forward and reverse bias and the current-voltage characteristics curve of the diodes were obtained. The slope of the graph at the most linear part of the graph in the negative axis was used to evaluate the shunt resistance. The series resistance was evaluated from the forward bias I-V characteristic curve at the linear portion of the curve. The saturation current density was also evaluated from the reverse bias I-V characteristic curve.

The current-voltage characteristics measurements were also used to obtain the non ideal factor, A of the diodes. A graph of current versus voltage was plotted. And the dark saturation current density, J_o was obtained.

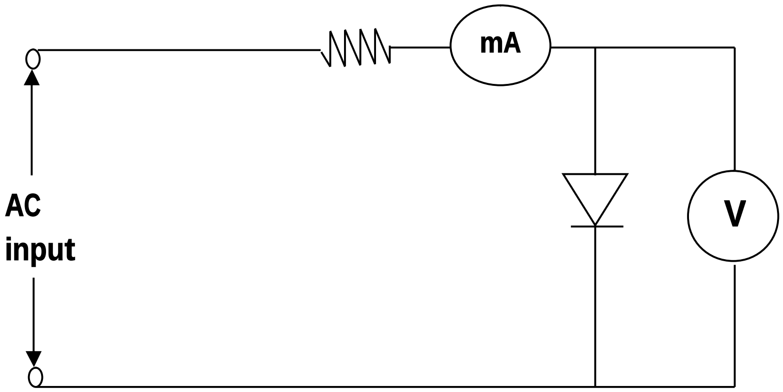

Figure 3.1. Schematic circuits diagram of current-voltage characteristics of the fabricated Cu/Cu_2O diode.

The current-voltage characteristics measurement for standard germanium IN270 diode was also taken. This was carried out so as to compare the values obtained from the fabricated Cu/Cu_2O diodes with that obtained from the market.

A graph of current against voltage was also plotted in the positive and negative axes and the current-voltage characteristics curve for the germanium diode was obtained.

3.9 HALF WAVE RECTIFICATION.

The fabricated Cu/Cu_2O diodes samples were used for half-wave rectification. A sinusoidal voltage wave from the resistor was observed from the oscilloscope. The frequency of the oscilloscope was set at 50Hz when the half-wave rectification was set up. The voltage wave form was observed and recorded.

3.10 FULL WAVE RECTIFICATION WITH THE USE OF CENTRE TAP TRANSFORMER CIRCUIT

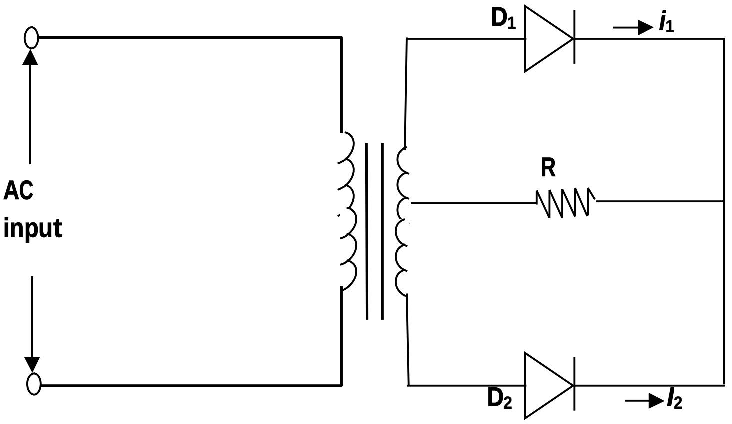

Figure 3.2. Full wave rectification with the use of centre tap transformer circuit.

The above diagram represents the full wave rectification with the use of centre tap transformer circuit. Where i_1 is the current through the diode D_1, i_2 is the current through the D_2 diode, AC is the input voltage source and R is the resistor.

The fabricated Cu/Cu_2O diodes were used in the full wave rectification with the use of centre tap transformer circuit. The rectification waveforms were observed and recorded.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 RESULTS

4.1.1 Oxidation Process

In an attempt to fabricate good diodes that have very high performance, care was taken in the selection of the copper material to be used. On the onset, copper of 99.98% purity was oxidized at constant temperature of 950^{o}C for variable time of three to five minutes and annealed at 500^{o}C for one hour and one and half hour. After oxidation, it was observed that the oxidized copper foil turn black which indicate the present of CuO on top of Cu_2O.

4.1.2 Rectifying Properties

The rectifying properties of the fabricated diodes were observed to be very poor when only one Cu/Cu_2O structure was used as in figure 4.9 below. However, when the samples were oxidized for four minutes and annealed for one hour, it was observed that the fabricated diodes of this material when three Cu/Cu_2O structures were used have the highest performance as in figures 4.10 and 4.11.

The fabricated diodes were used to measure the current – voltage characteristics and the results obtained are tabulated in tables 4.1a to 4.8b. This was also used for half wave and full wave rectification and the wave forms were shown in figures 4.10 and 4.11 respectively.

Table 4.1a Forward bias J-V characteristics of sample $A_{1.}$

S/No.	V(v)	I(mA)	J(mAcm^{-2})	J(Acm^{-2})
1.	0.200	0.000	0.000	0.000
2.	0.813	0.200	0.200	2.00 X 10^{-4}
3.	1.100	0.400	0.400	4.00 X 10^{-4}
4.	1.200	0.600	0.600	6.00 X 10^{-4}
5.	1.500	0.800	0.800	8.00 X 10^{-3}
6.	1.727	1.000	1.000	1.00 X 10^{-3}
7.	1.958	1.300	1.300	1.30 X 10^{-3}

Table 4.1b Reverse bias J-V characteristics of sample $A_{1.}$

S/No.	V(v)	I(mA)	I(A)	J(Acm^{-2})
1.	-0.700	-0.003	-3.00 X 10^{-6}	-3.00 X 10^{-6}
2.	-1.100	-0.005	-5.00 X 10^{-6}	-5.00 X 10^{-6}
3.	-1.977	-0.007	-7.00 X 10^{-6}	-7.00 X 10^{-6}

Table 4.2a Forward bias J-V characteristics of sample A_2.

S/N<u>o</u>.	V(v)	I(mA)	J(mAcm^{-2})	J(Acm^{-2})
1.	0.180	0.000	0.000	0.000
2.	0.908	0.200	0.200	2.00 X 10^{-4}
3.	1.208	0.400	0.400	4.00 X 10^{-4}
4.	1.403	0.600	0.600	6.00 X 10^{-4}
5.	1.540	0.800	0.800	8.00 X 10^{-3}
6.	1.686	1.000	1.000	1.00 X 10^{-3}
7.	1.951	1.600	1.600	1.60 X 10^{-3}

Table 4.2b Reverse bias J-V characteristics of sample A_2.

S/N<u>o</u>.	V(v)	I(mA)	I(A)	J(Acm^{-2})
1.	-0.2000	-0.0012	-1.20 X 10^{-6}	-1.20 X 10^{-6}
2.	-1.2000	-0.0020	-2.00 X 10^{-6}	-2.00 X 10^{-6}
3.	-1.9650	-0.0040	-4.00 X 10^{-6}	-4.00 X 10^{-6}

Table 4.3a Forward bias J-V characteristics of sample A_3.

S/No.	V(v)	I(mA)	J($mAcm^{-2}$)	J(Acm^{-2})
1.	0.150	0.000	0.000	0.000
2.	0.640	0.400	0.400	$4.00 X 10^{-4}$
3.	0.860	0.600	0.600	$6.00 X 10^{-4}$
4.	1.040	0.800	0.800	$8.00 X 10^{-4}$
5.	1.230	1.000	1.000	$1.00 X 10^{-3}$
6.	1.360	1.200	1.200	$1.20 X 10^{-3}$

Table 4.4a Forward bias J-V characteristics of sample A_4.

S/No.	V(v)	I(mA)	J($mAcm^{-2}$)	J(Acm^{-2})
1.	0.170	0.000	0.000	0.000
2.	0.200	0.100	0.100	$1.00 X 10^{-4}$
3.	0.665	0.200	0.200	$2.00 X 10^{-4}$
4.	0.992	0.400	0.400	$4.00 X 10^{-4}$
5.	1.236	0.600	0.600	$6.00 X 10^{-3}$
6.	1.409	0.800	0.800	$8.00 X 10^{-4}$
7.	1.570	1.000	1.000	$1.00 X 10^{-3}$
8.	1.742	1.200	1.200	$1.20 X 10^{-3}$
9.	1.844	1.400	1.400	$1.40 X 10^{-3}$
10.	1.949	1.600	1.600	$1.60 X 10^{-3}$

Table 4.4b Reverse bias J-V characteristics of sample A_4.

S/No.	V(v)	I(mA)	I(A)	J(Acm^{-2})
1.	-0.9500	-0.0016	-1.60×10^{-6}	-1.60×10^{-6}
2.	-1.4000	-0.0020	-2.00×10^{-6}	-2.00×10^{-6}
3.	-1.9560	-0.0040	-4.00×10^{-6}	-4.00×10^{-6}

Table 4.5a Forward bias J-V characteristics of sample B_1.

S/No.	V(v)	I(mA)	J($mAcm^{-2}$)	J(Acm^{-2})
1.	0.466	0.000	0.000	0.000
2.	0.580	0.200	0.200	2.00×10^{-4}
3.	1.040	0.500	0.500	5.00×10^{-4}
4.	1.200	0.600	0.600	6.00×10^{-4}
5.	1.330	0.800	0.800	8.00×10^{-4}
6.	1.410	0.900	0.900	9.00×10^{-4}

Table 4.5b Reverse bias J-V characteristics of sample B_1.

S/No.	V(v)	I(mA)	I(A)	J(Acm^{-2})
1.	-0.9700	-0.0023	-2.30 X 10^{-6}	-2.30 X 10^{-6}
2.	-1.4000	-0.0042	-4.20 X 10^{-6}	-4.20 X 10^{-6}
3.	-1.6600	-0.0069	-6.90 X 10^{-6}	-6.90 X 10^{-6}

Table 4.6a Forward bias J-V characteristics of sample B_2.

S/No.	V(v)	I(mA)	J(mAcm^{-2})	J(Acm^{-2})
1.	0.180	0.000	0.000	0.000
2.	0.550	0.100	0.100	1.00 X 10^{-4}
3.	0.750	0.200	0.200	2.00 X 10^{-4}
4.	0.900	0.300	0.300	3.00 X 10^{-4}
5.	1.100	0.400	0.400	4.00 X 10^{-4}
6.	1.200	0.500	0.500	5.00 X 10^{-4}
7.	1.400	0.600	0.600	6.00 X 10^{-4}
8.	1.550	0.700	0.700	7.00 X 10^{-4}
9.	1.650	0.800	0.800	8.00 X 10^{-4}

Table 4.6b Reverse bias J-V characteristics of sample B_2.

S/No.	V(v)	I(mA)	I(A)	J(Acm^{-2})
1.	-0.4000	-0.0040	-4.00×10^{-6}	-1.20×10^{-6}
2.	-1.1000	-0.0050	-5.00×10^{-6}	-5.00×10^{-6}
3.	-1.7200	-0.0057	-5.70×10^{-6}	-5.70×10^{-6}

Table 4.7a Forward bias J-V characteristics of sample B_3.

S/No.	V(v)	I(mA)	J($mAcm^{-2}$)	J(Acm^{-2})
1.	0.160	0.000	0.000	0.000
2.	0.200	1.000	1.000	1.00×10^{-3}
3.	0.235	2.000	2.000	2.00×10^{-3}
4.	0.270	3.000	3.000	3.00×10^{-3}
5.	0.306	4.000	4.000	4.00×10^{-3}
6.	0.340	5.000	5.000	5.00×10^{-3}
7.	0.380	6.000	6.000	6.00×10^{-3}
8.	0.420	7.000	7.000	7.00×10^{-3}
9.	0.470	8.000	8.000	8.00×10^{-3}

Table 4.7b Reverse bias J-V characteristics of sample B_3.

S/No.	V(v)	I(mA)	I(A)	J(Acm^{-2})
1.	-0.05000	-0.00560	-5.60 X 10^{-6}	-5.60 X 10^{-6}
2.	-0.15000	-0.00147	-1.47 X 10^{-6}	-1.47 X 10^{-6}
3.	-0.33500	-0.0020	-2.00 X 10^{-6}	-2.00 X 10^{-6}

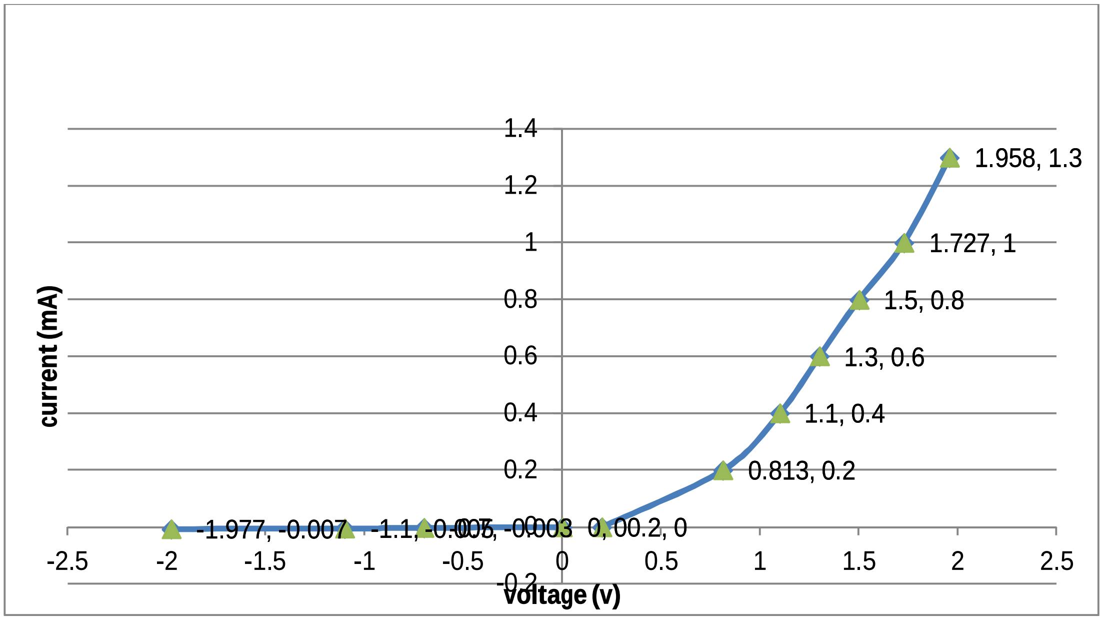

Figure 4.1. J-V characteristics of sampleA_1.

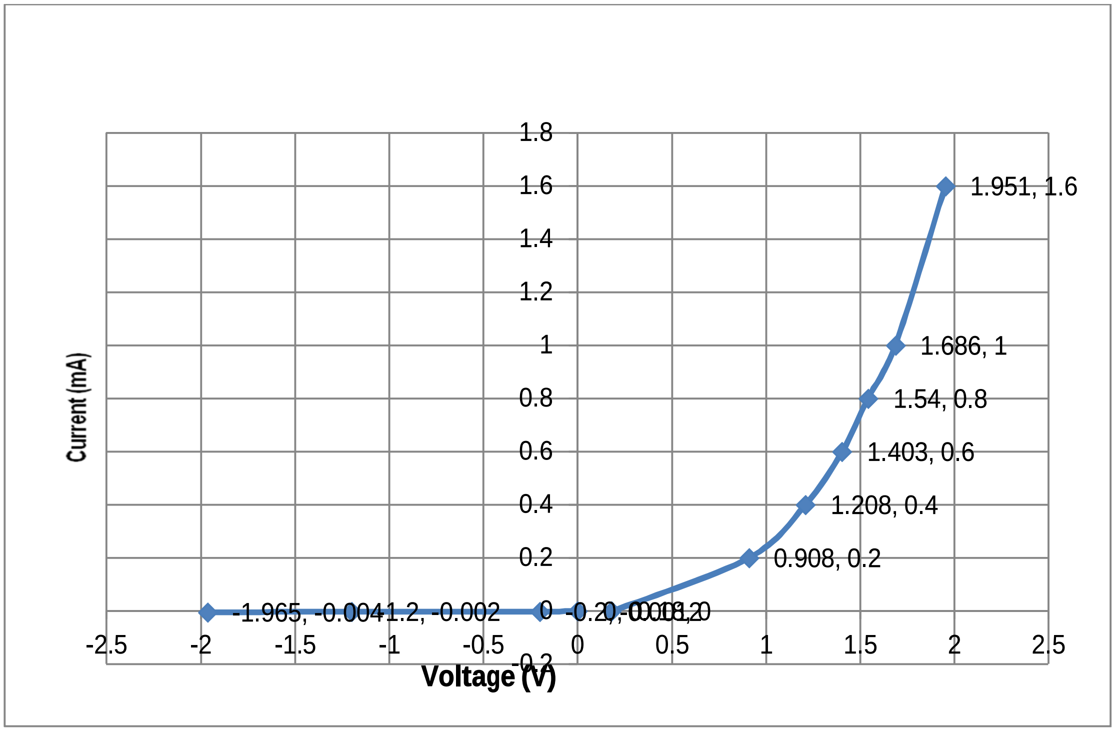

Figure 4.2. J-V characteristics of sampleA$_{2}$.

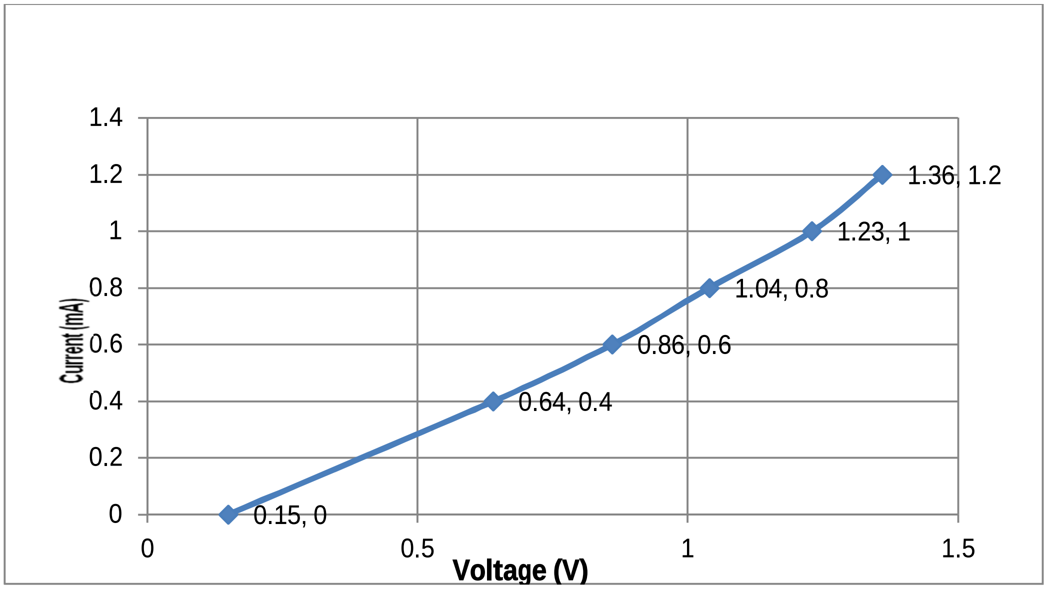

Figure 4.3. J -V characteristics of sampleA$_{3}$.

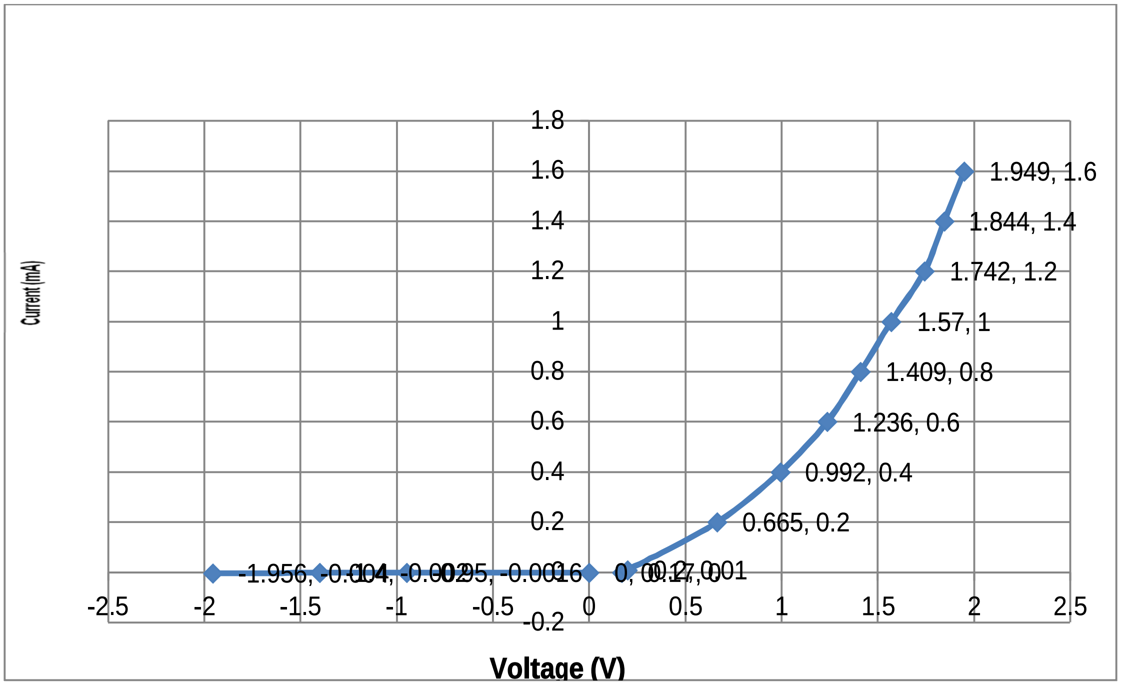

Figure 4.4. J -V characteristics of sampleA_4.

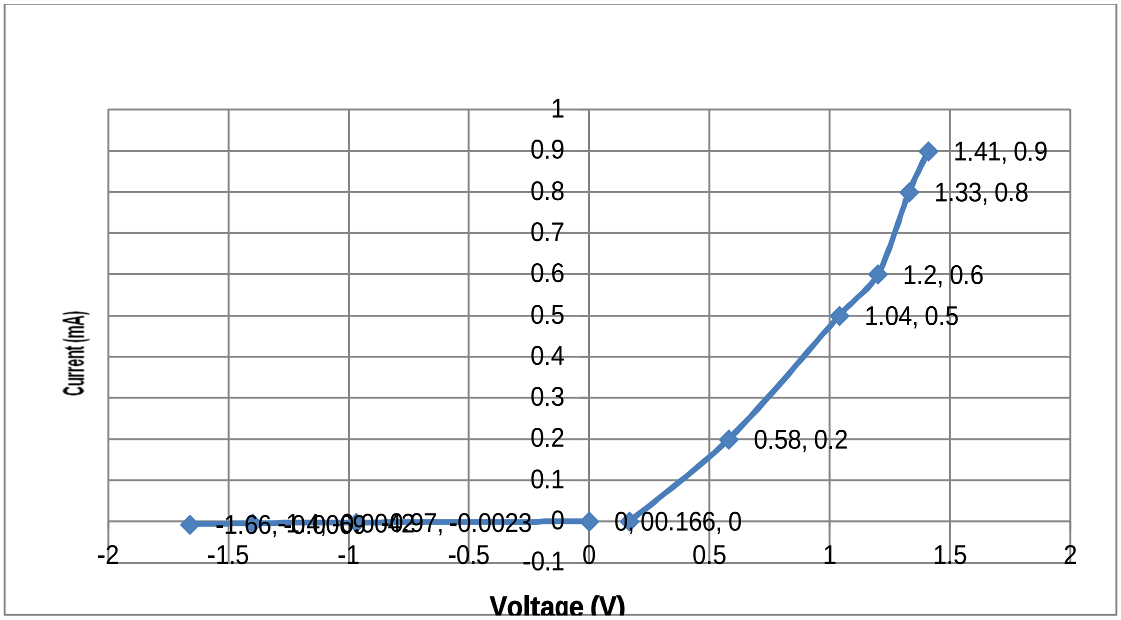

Figure 4.5. J -V characteristics of sample B_1.

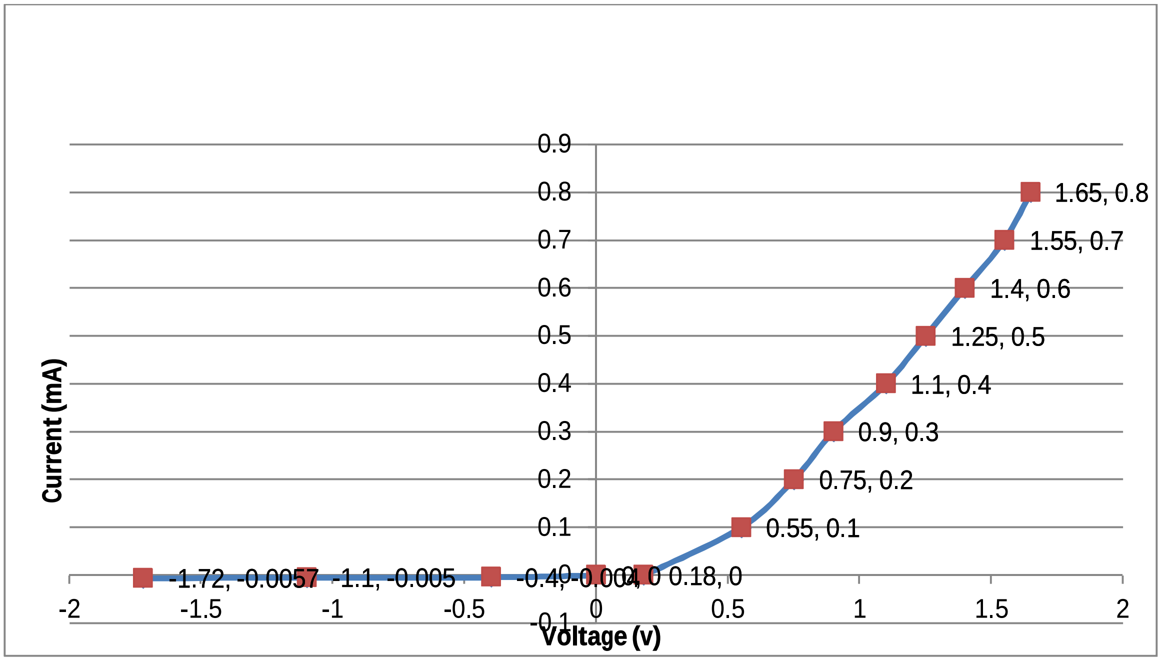

Figure 4.6. J -V characteristics of sampleB2.

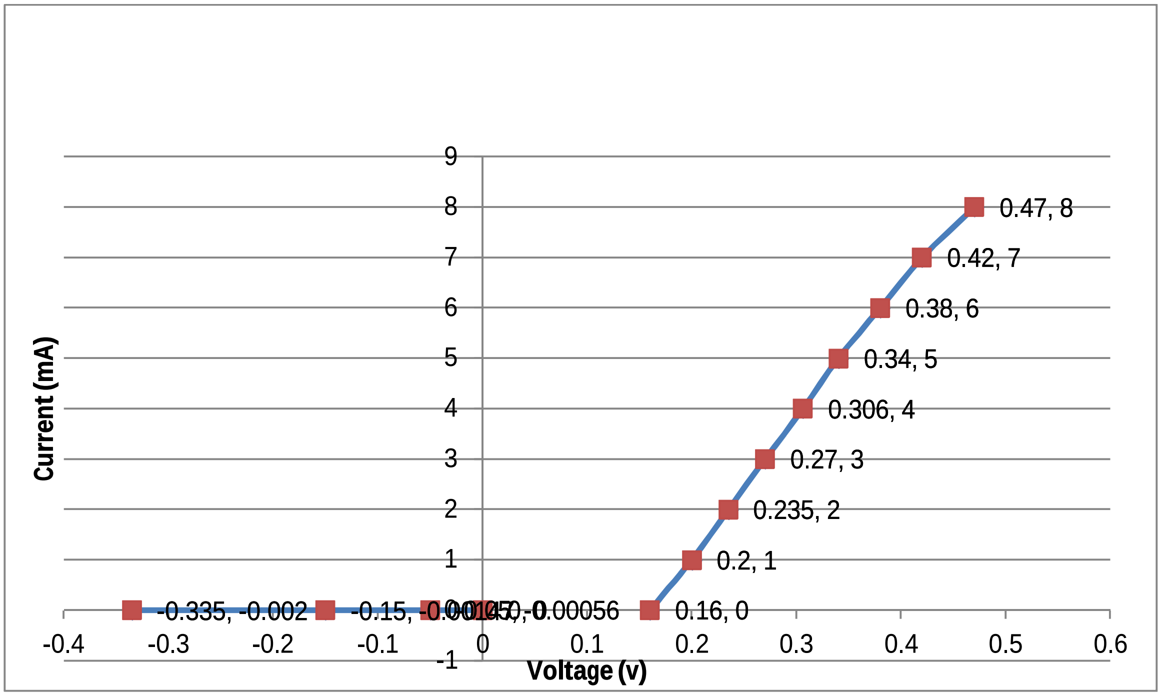

Figure 4.7. J -V characteristics of sample B3.

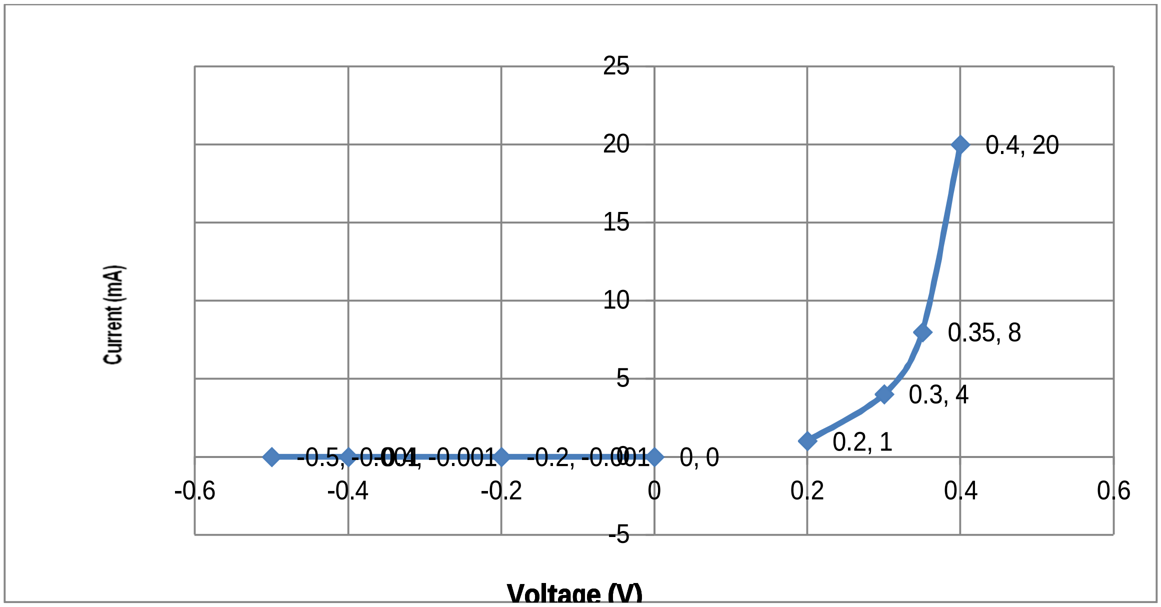

Figure 4.8. J V characteristics of germanium 1N270 diode.

Table 4.8a Rectifying properties of the fabricated Cu/Cu_2O diode.

S/No.	Forward resistance (KΩ)	Reverse resistance (MΩ)
Sample 1.	71.44	0.47
Sample 2.	71.43	0.47
Sample 3.	71.43	0.46
Sample 4	71.42	0.45

Table 4.8b Rectifying resistances of germanium 1N270 diode.

S/No.	Forward resistance (KΩ)	Reverse resistance (MΩ)
1.	71.70	0.50

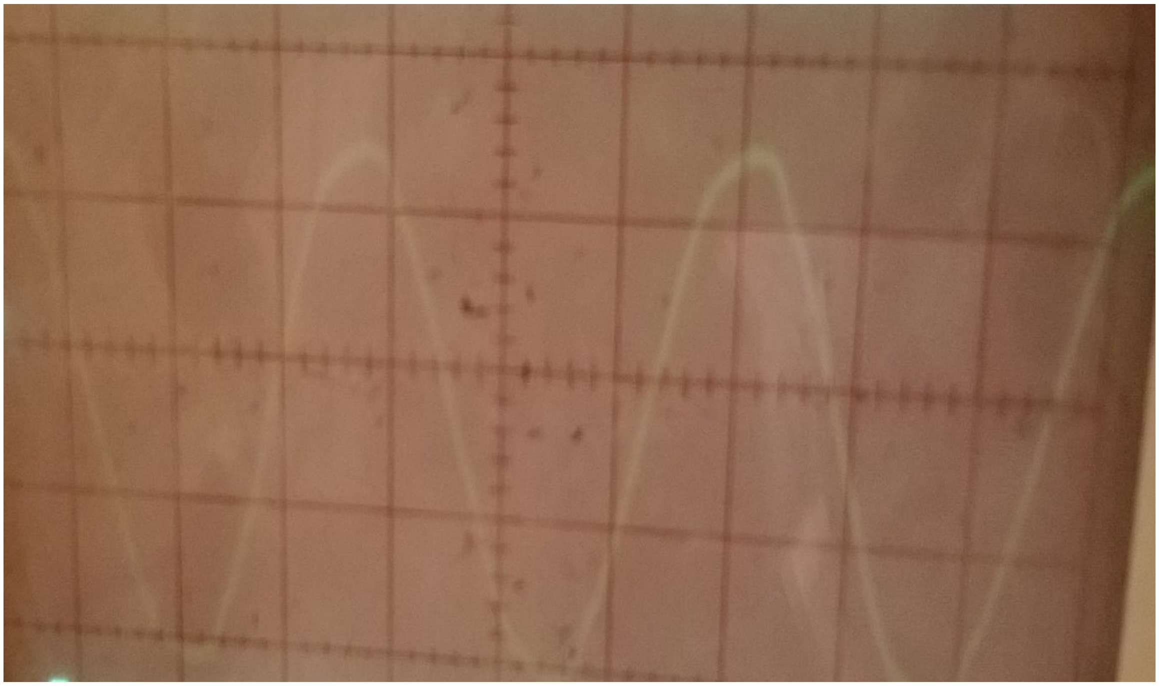

Figure 4.9. Poor sine wave rectified wave form signal of the fabricated diode.

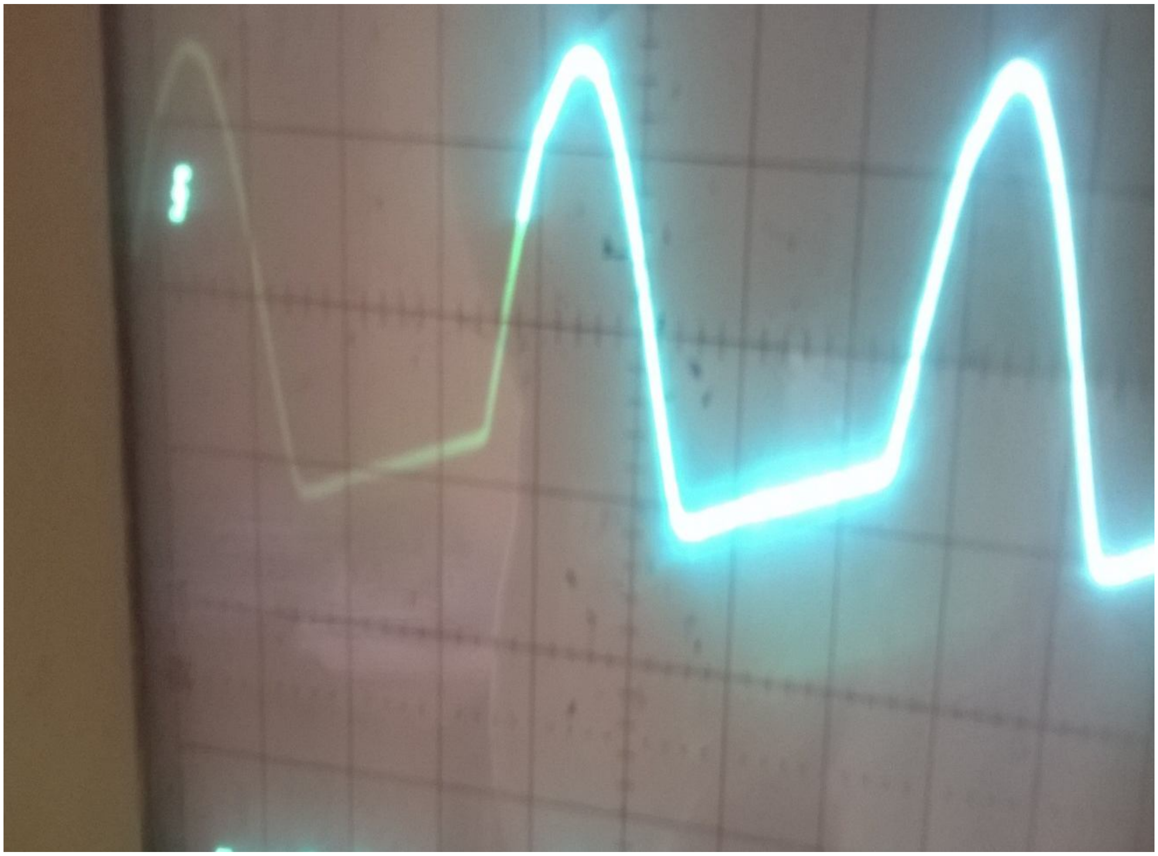

Figure 4.10. Half wave rectification wave form signal of the fabricated diode.

Figure 4.11. Full wave rectification wave form signal of the fabricated diode.

4.2 DISCUSSIONS

4.2.1 Oxidation Processes

The surfaces of the copper samples became smooth and bright after it had been dipped in the solution of sodium persulphate, and rinsed in distilled water. When the oxidation time was attained, the oxidized samples were brought out gently from the furnace and immediately quenched in cold distilled water to stop further oxidation.

The oxidized samples were annealed at 500^{o}C. This annealing became imperative because of the disorder caused to the samples resulting from the high temperature oxidation.

The samples were oxidized at constant temperature but at variable time. Black substances were observed on the surface of the samples after oxidation and annealing process were completed. This indicates the presence of copper (II) oxide (CuO).

After the first chemical etching, reddish-brown colour was observed which indicates the presence of copper (I) oxide (Cu_2O). Whereas the second chemical etching removed Cu_2O on one side of the samples and revealed copper.

It was observed that temperature and time played very crucial role in the oxidation process. The oxidation temperature is proportional to the amount of copper (I) oxide deposited on copper foil. However, the fragile nature of the samples was observed when they were oxidized at a very high temperature (above 1000^oC) for longer period of time.

Copper (I) oxides have been identified to be stable at limited ranges of temperature and high oxygen pressure. During thermal oxidation, copper (I) oxide was formed first and sufficiently long oxidation time, copper (II) oxide was also formed on top of copper (I) oxide.

4.2.2 Current – Voltage Characteristics

The external and internal parameters of the diodes were studied using the current–voltage characteristics curves. The values of the forward bias J-V characteristics of the fabricated diodes were shown in tables 4.1a, 4.2a, 4.3a, 4.4a, 4.5a, 4.6a and 4.7a whereas the reverse bias J-V characteristics values were shown in tables 4.1b, 4.2b, 4.4b, 4.5b, 4.6b and 4.7b. The graphs of these values were plotted as shown in figures 4.1 to 4.7. These were compared with that of germanium 1N270 as in figure 4.8 above.

Some of these internal parameters are the diode non–ideal factor, A and the dark saturation current density, J_o. These parameters help in determining the limiting loss mechanism in the diodes. The external parameter is the series resistance, R_S. These parameters provide the output performance of the fabricated diodes.

The diode non-ideal factor, A, was determined to be 5.16 using the equation:

$$A = \frac{q}{kT}\left[\frac{V_2 - V_1}{In\left(\frac{J_2}{J_1}\right)}\right]$$

The degrees of perfection of a diode is normally determines by the diode non-ideal factor, A. For a perfect diode junction A=1. For a practical commercial silicon p-n junction diode, A has values in the range 1.2 to 1.6 (Martin, 1982) whereas for germanium, A is equal to 2.4.

The saturation current density, J_o, is the sum of the thermally generated current density in the n and p region of the diode materials in the dark and it was determined from the J-V graph to be 3.5 X 10^{-6} Acm^{-2}. This was obtained when large negative voltage was applied across the diode in the dark. For practical silicon p-n junction diodes, $J_o \approx 7.6$ X 10^{-12} Acm^{-2} and $J_o \approx 3.2$ X 10^{-5} Acm^{-2} for germanium.

The series resistance, R_S, is the ratio of the change in voltage to the change in current of the reverse bias and it was determined from the graph to be 197.9kΩ.

4.2.3 Rectifying Properties of the Fabricated Cu/Cu_2O Diodes

In an attempt to fabricate good diodes that have very high performance, care was taken in the selection of the copper material to be used. On the onset, copper of 99.98% purity was oxidized at constant temperature of 950°C for variable time of three to five minutes and annealed at 500°C for one hour. The rectifying properties of the fabricated diodes were observed to be very poor when only one Cu/Cu_2O structure was used as in figure 4.9 above. However, when the samples were oxidized for four minutes and annealed for one hour, it was observed that the fabricated diodes of this material when three Cu/Cu_2O structures were used have the highest performance as in figures 4.10 and 4.11.

However, the values of the forward and the reverse resistances of the fabricated Cu/Cu_2O diodes were obtained as shown in table 4.8a above. These were compared with that obtained from germanium 1N270 diode as shown in table 4.8b.

CHAPTER FIVE

SUMMERY, CONCLUSION AND RECOMMENDATIONS

5.1 SUMMERY

The fabrication of Cu/Cu_2O diodes was carried out using partial thermal oxidation of high purify copper foil (99.98% purity, 0.1mm thickness) at a constant temperature of 950^oC with variation in time between three to five minutes. The best of the oxidized samples were selected and annealed at reduced temperature of 500^oC. The chemical etching process was carried out to remove the CuO and Cu_2O layer on one side of the surface to obtain a Cu/Cu_2O structure. The two terminals were formed using silver paste.

The current-voltage characteristics of the fabricated diodes were studied and analyzed. These were compared with the standard germanium diode. The graph of both characteristics were plotted and analyzed.

The forward and reverse resistances of both the fabricated diodes and standard germanium diode were measured, recorded and compared. The half and full wave rectification of the fabricated diodes were observed and recorded from the oscilloscope.

The diode series resistance, $R_{S,}$ the diode non-ideal factor and the dark saturation current density were evaluated and recorded.

5.2 CONLUSION

It was observed from this study that the performance of the fabricated diode was enhanced only when the number of the basic structure, Cu/Cu_2O, was increased from one to three**.** The rectifying properties of the fabricated diodes were observed to be very poor when only one Cu/Cu_2O structure was used as in figure 4.10. However, when the samples were oxidized for four minutes and annealed for one hour, it was observed that the fabricated diodes of this material when three Cu/Cu_2O structures were used have the highest performance as in figures 4.10 and 4.11 above. The average series resistance, R_S was evaluated to be 197.9kΩ while the diode non-ideal factor, A, and the saturation current density, J_o were measured to be 5.16 and 3.5 X 10^{-6} Acm^{-2} respectively.

5.3 RECOMMENDATIONS

It is recommended that;

(i) other methods of the formation of the Cu/Cu_2O structure like sputtering and electro-deposition should be tried and the results compared with the method used in this research,

(ii) thermal oxidation of copper should be performed in pure oxygen with the means of controlling its pressure instead of the atmospheric oxygen content used for the Cu oxidation in this work,

(iii) the number of the basic elements joined together can be increased to four and above and their resistances and their rectifying properties compared with the results obtained in this work.

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APPENDICES

PROPERTIES OF Cu_2O

Band gap	2.0 eV
Electron affinity	3.0 eV
Crystal structure	simple cubic
Lattice constant	4.27 Å
Melting point	$1.235^{o}C$
Density	$6.0\ gcm^{-2}$
Thermal expansion coefficient	$3.5 \times 10^{-6}\ k^{-1}$
Conductivity	p-type

EVALUATION OF J_O AND A

In general, the junction diode current equation is

$$J = J_o [\exp (\frac{qv}{AKT}) - 1]$$

For a forward bias of more than 0.1 V or so, the approximate equation becomes

$$J = J_o \exp (\frac{qv}{AKT})$$

At two points on the I-V curve, at forward bias portion, we have;

$$J_1 = J_o \exp (\frac{q\,V_1}{AkT})$$

and $$J_2 = J_o \exp (\frac{q\,V_2}{AkT})$$

hence, $$\frac{J_2}{J_1} = \exp[\frac{q}{AkT} (V_2 - V_1)]$$

and $$A = \frac{q}{kT} [\frac{V_2 - V_1}{In\left(\frac{J_2}{J_1}\right)}]$$

or $$A = 38.7[\frac{V_2 - V_1}{In\left(\frac{J_2}{J_1}\right)}]$$

where $\frac{q}{kT}$ = 38.7 V^{-1} at room temperature

SAMPLE

A_1 ------ number of basic elements joined together is 2, oxidation temperature is 950°C, oxidation time is 5 minutes, annealing temperature is 500°C, annealing time is 1 hour and surface area is $1cm^2$.

A_2 ------ number of basic elements joined together is 2, oxidation temperature is 950°C, oxidation time is 5 minutes, annealing temperature is 500°C, annealing time is 1½ hour and surface area is $1cm^2$.

A_3 ------ number of basic elements joined together is 2, oxidation temperature is 950°C, oxidation time is 3 minutes, annealing temperature is 500°C, annealing time is 1 hour and surface area is $1cm^2$.

A_4 ------ number of basic elements joined together is 2, oxidation temperature is 950°C, oxidation time is 3 minutes, annealing temperature is 500°C, annealing time is 1½ hour and surface area is $1cm^2$.

B_1 ------ number of basic elements joined together is 3, oxidation temperature is 950°C, oxidation time is 5 minutes, annealing temperature is 500°C, annealing time is 1 hour and surface area is $1cm^2$.

B_2 ------ number of basic elements joined together is 3, oxidation temperature is 950°C, oxidation time is 5 minutes, annealing temperature is 500°C, annealing time is 1½ hour and surface area is $1cm^2$.

B_3 ------ number of basic elements joined together is 4, oxidation temperature is 950°C, oxidation time is 5 minutes, annealing temperature is 500°C, annealing time is 1hour and surface area is $1cm^2$.