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Current-Voltage Characteristics and Photoresponse of Metal Al_2O_3 Metal Devices

K. SINGH, S.N.A. HAMMOND
Department of Physics
University of Science and Technology
Kumasi, Ghana
West Africa

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Abstract

Thin films (35 Å) of Al_2O_3 on glass slides have been used for the fabrication of $Al/Al_2O_3/Al, Ag/Al_2O_3/Al$ and $Cu/Al_2O_3/Al$ devices. The room temperature current-voltage characteristics and the dependence of current densities of these devices at various wavelength (λ) of light were measured. The results obtained on current density and photocurrent show that Al_2O_3 films have the potential for wider applications like antireflective coatings or treatments in photovoltaic devices, transparent insulation materials, and optical trapping surfaces in many electronic devices.

1. Introduction

Schottky barrier diodes have been under practical consideration since early 1930s and its transport mechanisms have been the subject of much theoretical research [1-3]. Most of the recent on-going research on Schottky barrier diodes are mainly biased towards their electrical properties. The barrier height and current transport phenomena which mostly relates to their electronic applications [4] have been reviewed by a number of research workers [5-9].

A great deal of work, both theoretical and experimental, has been done with the aim of providing a quantitative explanation of tunneling phenomena and information on fabrication technique for device applications [10-15]. Frenkel [16] has reported his approximate analysis of electron tunneling through thin insulating film. However, it was Sommerfeld and Bethe [17] who were the first to make a theoretical study of the phenomenon of tunneling effects through Metal-insulator-metal devices. They considered cases of high and low voltages and subsequently derived equations for the current density transmitted by rectangular barrier. It was also demostrated by Fisher and Giaever [18] that for small voltages the current through the insulator film is proportional to the voltage which shows that the low voltage resistance of the insulator is ohmic. Results obtained for high voltages showed however, that the I-V relationship was not linear.

A trapezoidal energy barrier was proposed by Fowler [19]. Later, Leweki et.al. [20] confirmed this and showed further that for insulator thickness in the range 30-50 Å, the trapezoidal model could adequately explain the photoresponse and that the barrier energies could be determined directly from photoresponse measurements.

Kadlec and Gundlach [21] reported a transient phenomena and their effect on the insulator barrier height in $Al/Al_2O_3/Al$ structures at temperatures 100 and 300 K. They showed that the application of a voltage of either polarity causes an increase of the barrier; this change is practically permanent at low temperatures but can be removed by annealing the sample to room temperature (300 K).

However, transient effects in tunneling structures at 300 K were first reported by Fisher and Giaever [18]. Similar results were obtained by Flannery and Pollack [22].

The utilization of Metal/Al_2O_3/Metal devices for solar application will be very attractive because of the apparent simplicity of these systems. In order to make wider application of Al_2O_3 films prepared by oxidation method, an attempt has been made, as first step, to study the photoresponse of $Al/Al_2O_3/Al$, $Ag/Al_2O_3/Al$ and $Cu/Al_2O_3/Al$ devices. The current-voltage characteristics of these devices were also measured.

2. Theory

In this work the Photoelectric technique has been used to study the variation of photocurrent with wavelength (λ) and the dependence of barrier height on the metal workfunction for these devices.

2.1. Photoelectric Method [23, 24]

The barrier height can be measured more directly and accurately by photoelectric measurements [25]. Photocurrent may be generated by illuminating a metal surface by using monochromatic light of energy $h\nu > \phi_b$, where ϕ_b is the potential barrier height. The basic setup for photoelectric measurement and energy-band diagram for photoexcited processes are shown in Figure 1.

The photocurrent per absorbed photon R as a function of the photon energy $(h\nu)$ is given by the Fowler theory [26]:

$$R \sim [T^2/(E_s - h\nu)^{1/2}] \cdot [x^2 + \pi^2 - (e^{-x} - e^{-2x} + e^{-3x} \cdots)], \tag{1}$$

where $h\nu_0$ is the barrier height $(q\phi_b)$, E_s is the sum of $h\nu_0$ and the Fermi energy measured from the bottom of the metal conduction band and $x = h(\nu - \nu_0)/kT$. Under the condition that $E_s >>> h\nu$, and $x > 3$, Equation (1) reduces to

$$R \sim (h\nu - h\nu_0)^2 \quad \text{for } h(\nu - \nu_0) > 3kT \tag{2}$$

or

$$R^{1/2} \sim h(\nu - \nu_0). \tag{3}$$

When the squareroot of the photocurrent is plotted as a function of photon energy, a straight line should be obtained and the extrapolated value on the energy axis should give directly the barrier height (Fowler Plot).

3. Experimental Procedures

3.1. Preparation of Al_2O_3 Film

Thoroughly cleaned and dried three glass substrates of dimension $4.0 \times 2.0cm$ were used for making the sample devices. First of all, the Aluminium-stripe was evaporated in a vacuum coating unit at about 10^{-5} torr from a tungeston boat onto the cleaned and dried glass slides. The Al-oxide was formed on the surface of the Aluminium-stripes by oxidation for about 30 minutes in an oven at $70°C$.

3.2. Fabrication of Metal/ Al_2O_3 /Metal Devices

The evaporation of Al, Ag and Cu as top metals on the three Al_2O_3/Al substrates were done in the vacuum coating unit at about 10^{-5} torr. The Al_2O_3 thicknesses of the samples were determined by capacitance measurements assuming a relative dielectric constant of 8.4 for the Al_2O_3 layer and thicknesses were found to be between 32 and 35 Å.

3.3. Photoelectric Measurement

The experimental setup is shown in Fig. 1. For each filter used, the corresponding currents were read in the electrometer. Four different filters, namely red, yellow, green and violet were used. A 200 W mercury lamp was used as source of light.

3.4. Current-Voltage Measurement

The point contacts were made to the sample and the samples were biased from 0.5 V to 2.5 V at an interval of 0.5 V using Wien Monoreg power supply. For every biased voltage the corresponding voltage-induced current was measured using Keithley Electrometer Model 6100.

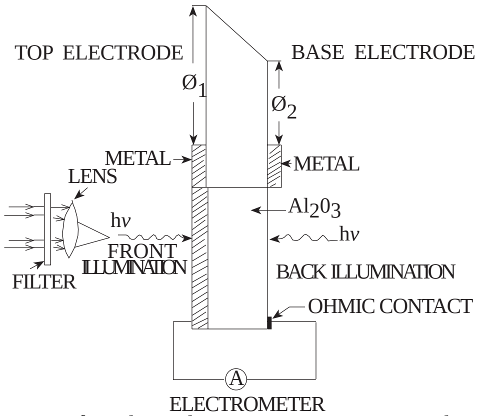

Figure 1. Basic setup for photoelectric measurement and energy-band diagram

4. Results

4.1. Variation of Photocurrent with Wavelength (λ)

The variations of photocurrent with wavelength (λ) for $Al/Al_2O_3/Al$ $Ag/Al_2O_3/Al$ and $Cu/Al_2O_3/Al$ devices were measured and presented in Table 1. Figure 2 shows the variation of photocurrent per absorbed photon with energy of photon for the three devices.

The variation of $R^{1/2}$ with the photon energy as a function of wavelength (λ) was calculated using Equation (3) and is given in Table 2 and presented in Fig. 3 for all three devices. At $R = 0$, linear regression barrier heights of 1.66, 1.72 and 1.80 eV.

Table 1. Variation of photocurrent with wavelength λ for the three devices

Colour	$\lambda/\mathring{A}$	Energy/eV	$I_1 A \times 10^{-8}$ $Al/Al_2O_3/Al$	$I_2 A \times 10^{-8}$ $Ag/Al_2O_3/Al$	$I_3 A \times 10^{-8}$ $Cu/Al_2O_3/Al$
Red	6562	1.893	0.1700	0.0600	0.0120
Yellow	5890	2.109	0.5800	0.2800	0.0800
Green	5278	2.354	1.6200	0.8700	0.4100
Violet	4330	2.869	6.2000	3.6600	1.7200

Table 2. Variation of $R^{1/2}$ with energy of photon

Energy	$R^{1/2} \times 10^{-4}$		
	$Al/Al_2O_3/Al$	$Ag/Al_2O_3/Al$	$Cu/Al_2O_3/Al$
1.893	0.3000	0.1782	0.0797
2.109	0.5249	0.3647	0.1949
2.354	0.8304	0.6085	0.4178
2.869	1.4714	1.1305	0.7750

A table of results showing the dependence of the barrier height on the metal workfunction for three devices is presented Table 3.

Table 3. Dependence of barrier height on the metal workfunction

Device	Workfunction of top metal (eV)	Barrier height
$Al/Al_2O_3/Al$	4.25	1.66
$Ag/Al_2O_3/Al$	4.30	1.72
$Cu/Al_2O_3/Al$	4.40	1.80

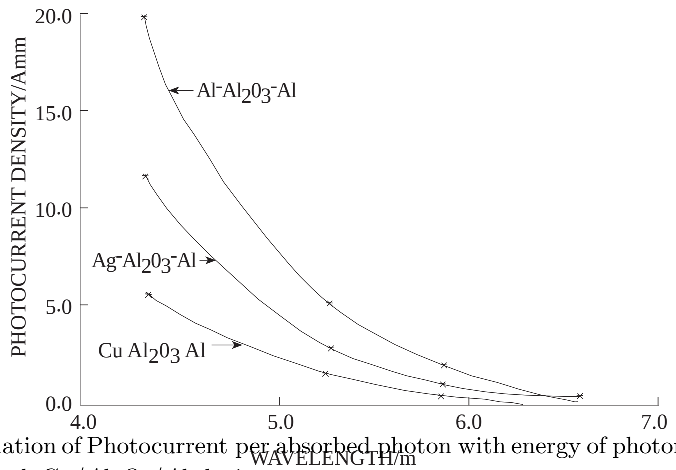

Figure 2. Variation of Photocurrent per absorbed photon with energy of photon for $Al/Al_2O_3/Al$, $Ag/Al_2O_3/Al$ and $Cu/Al_2O_3/Al$ devices

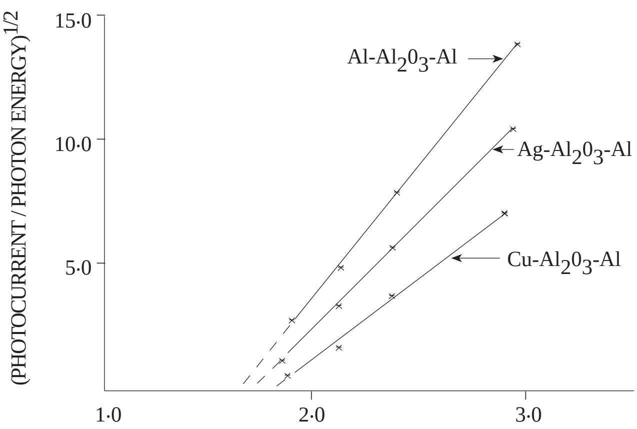

Figure 3. Variation of square root of photocurrent per incident photon with incident photon energy

4.2. Variation of Current Density with Applied Voltage

For the range of voltage applied on the devices, the current flow depends on the polarity of the applied voltage at the electrodes. Simon [27] has defined that with disimilar metals, the electrodes are reversed biased when the electrons are tunnelling from the electrode of lower work function to that of higher one. Similarly, the electrodes are forward biased when the electrode of lower work function is at the positive polarity of the applied voltage. Thus for electrons to tunnel from top electrode to base electrode, the measurement were taken for forward biased electrodes. The measured tunnelling current density with applied voltages are presented in Table 4, and are shown in Figs. 4a, 4b and 4c for $Al/Al_2O_3/Al$, $Ag/Al_2O_3/Al$ and $Cu/Al_2O_3/Al$, respectively.

Table 4. Variation of current density with applied voltage

Applied	Current density $J(Amm^{-2})$		
Voltage	$Al/Al_2O_3/Al$	$Ag/Al_2O_3/Al$	$Cu/Al_2O_3/Al$
0.5	5.4106×10^{-6}	4.9332×10^{-7}	1.7505×10^{-8}
1.0	7.0019×10^{-6}	6.3654×10^{-7}	3.0236×10^{-8}
1.5	1.0026×10^{-5}	8.2750×10^{-7}	4.4558×10^{-8}
2.0	1.3049×10^{-5}	1.1617×10^{-6}	7.6384×10^{-8}
2.5	1.5436×10^{-5}	1.4004×10^{-6}	1.1617×10^{-7}

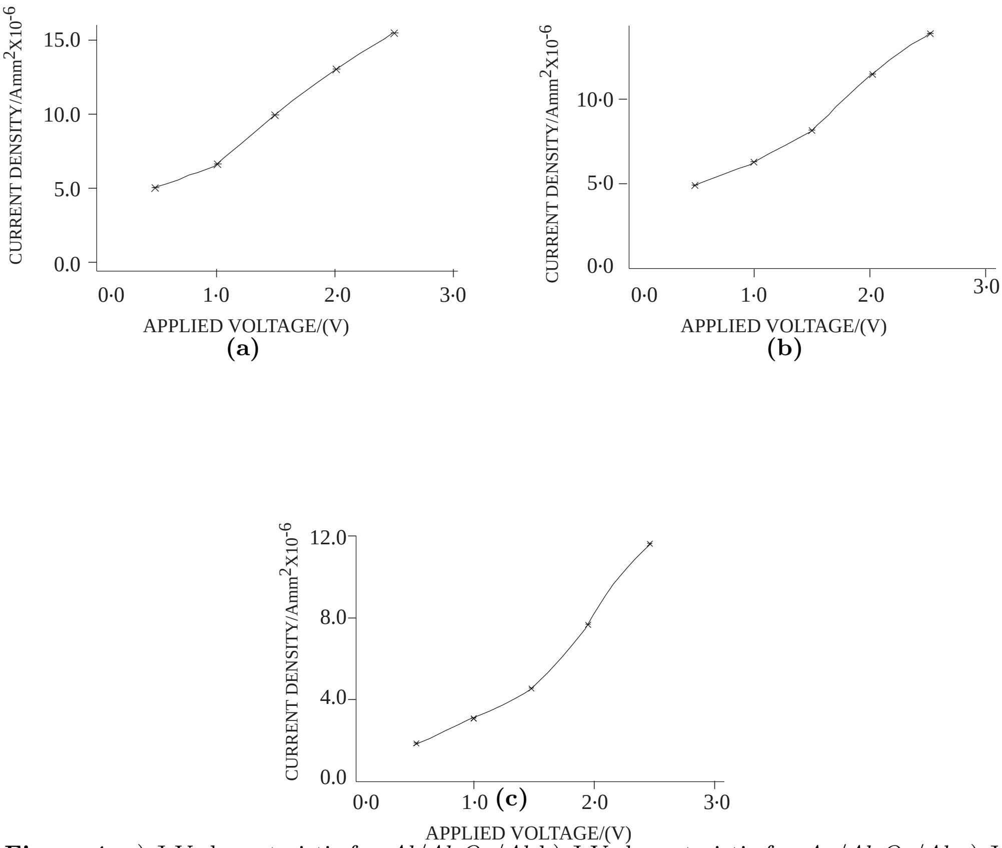

Figure 4. a) J-V characteristic for $Al/Al_2O_3/Al$ b) J-V characteristic for $Ag/Al_2O_3/Al$ c) J-V characteristic for $Cu/Al_2O_3/Al$

5. Discussion

Fig. 3 shows the square root of the photocurrent per incident photon plotted against the photon energy, which is typical with photon-emission data. This shows the energy range throughout which the photocurrent follows the Fowler relation [26].

The intercepts on the energy axis in Fig. 3 give the barrier heights between the top-metals - Al, Ag and Cu with the Al_2O_3 and this is the energy difference between the conduction band of the Al_2O_3 and the Fermi level of these metals if one assumes that the ratio of absorbed photons to incident photon is constant over the spectral range through which the straight lines are drawn. That is, the intercept gives the effective work function of the metals relative to the conduction band of the oxide with which they are in contact.

Results on photoresponse obtained show that metals with high work-functions gave higher barrier height than those with lower work-functions. It is evidently clear that the barrier height, which is a characteristic of a particular contact, is a function of a number of factors like image force, the workfunction of the metal, the presence of interfacial layer etc.

At relative high and intermediate voltages (3V and 0.5 V) the results obtained on J-V characteristics show that the current density is not linearly related to the applied voltage and might be due to trapping of charge carriers and the presence of space charges in the Al_2O_3 band gap.

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