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INVESTIGATION OF SOLAR CELLS BASED ON Cu_2O

Quarterly Progress Report for May 1—July 31, 1979

MASTER

By
Larry C. Olsen

September 7, 1979

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Joint Center for Graduate Study
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Richland, Washington

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Solar Energy

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Professor Larry C. Olsen

Joint Center for Graduate Study
University of Washington
Richland, Washington 99352

Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the Department of Energy.

ABSTRACT

Efforts during this quarter have involved a detailed study of photocurrent from Cu/Cu₂O Schottky barriers, development of a MBE system, and studies of reactively sputtered ZnO films. Optical constants were determined for Cu films as a function of film thickness and utilized to determine optimum AR coating thicknesses to maximize the photocurrent from Cu/Cu₂O cells. Using results of these analyses, an AM1 photocurrent of 7.4 mA/cm² has been obtained. Fabrication and purchasing of parts for a three-source MBE system has progressed well. Conductive and transparent ZnO films were deposited by reactively sputtering zinc. Films exhibiting a sheet resistance in the range of 10³ to 10⁵ Ω/□ have been deposited on quartz.

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1. INTRODUCTION

1.1 Objective Approach

The overall objective of this program is to develop low-cost solar cells based on Cu_2O . Emphasis will be placed on fabrication and characterization of MIS and heterojunction cell structures which have potential efficiencies greater than 10%.

1.2 Background Material

Cu_2O has a direct bandgap of 2.0 eV, can be grown in a straightforward manner by oxidizing copper, and is composed of abundant elements. The maximum possible AM1 photocurrent for Cu_2O is 17.3 mA/cm^2 . If we assume a structure can be fabricated which is equivalent to a homojunction, with $n = 1$, then the theoretical efficiency is $\approx 21\%$. If it is assumed that $n = 2$, then the maximum efficiency is $\approx 15\%$. It is assumed that $J_0 = 10^6 \exp(-E_g/nkT) \text{ A/cm}^2$ for both of these calculations.

1.3 Emphasis This Quarter

This quarter constitutes the first efforts of this program. Thus, much of the work relates to startup activity. Emphasis has been placed on improving photocurrent, modifying an existing evaporation system to provide a three-source MBE capability, and developing an approach to reactively sputtering ZnO . Key accomplishments of this quarter are:

1. Achievement of a photocurrent of 7.4 mA/cm^2 with a Schottky barrier;
2. Purchase and fabrication of parts required for MBE system;
3. Deposition of a ZnO film by reactive sputtering with a sheet resistance of $1.45 \times 10^3 \Omega/\square$.

2. THEORETICAL MODELING AND CALCULATIONS

During the first quarter, efforts concerning analytical studies have concentrated on calculations of the change in Gibb's free energy associated with several important reactions, and on calculations of expected photocurrents from Cu_2O solar cells.

2.1 Gibb's Free Energy Calculations

To provide a guide in selecting material components for Cu_2O MIS or heterojunction cell structures, calculations of the change in Gibb's free energy for several pertinent reactions have been conducted. Some possible cell structures of interest are shown in Table 1.

Values for the standard free energy of formation for several metal oxides are given in Table 2. In Cu_2O MIS structures, the M-I and I- Cu_2O interfaces need attention. For example, an interfacial layer of SiO_2 and metal of Mg does not appear attractive since Mg will reduce SiO_2 . On the other hand, Cu, Zn, Sb, and Mn would be compatible with SiO_2 interfacial layer. Since Sb and Mn have work functions below 4 eV, MIS structures based on these metals and SiO_2 will be investigated.

Heterojunction cell structures being considered are indicated in Table 1. The $\text{ZnO}/\text{Cu}_2\text{O}$ junction will be stable if a stoichiometric ZnO film is in contact with Cu_2O . If a Zn-rich region is adjacent to Cu_2O , however, then a reduction of Cu_2O would tend to occur leaving free copper at the interface. The reactions considered in Table 3 apply to the possible heterojunctions $\text{ZnS}/\text{Cu}_2\text{O}$ and $\text{SiC}/\text{Cu}_2\text{O}$. Consider ZnS reacting with Cu_2O (reaction No. 1). As indicated, the reaction can produce Cu_2S and ZnO. The associated ΔG is negative, but relatively small in absolute value. Reaction No. 1 tends to occur instead of No. 2. An interfacial region of Cu_2S and ZnO may not be prohibitive to good photovoltaic performance, however.

Results for Cu_2O and SiC suggest that formation of SiO_2 , free copper and carbon may occur. It would appear, however, that $\text{SiC}/\text{Cu}_2\text{O}$ heterojunctions are still worthy of investigation. The lattice constant of SiC is within 2% of that

Table 1
POSSIBLE Cu_2O CELL STRUCTURES

Cell Type	Cell Structure
MIS	AR (700 Å)
	Cu (40 Å)
	M (20 Å)
	I (20 Å)
	Cu_2O (1 to 10 μm)
M = Sb, Mg, Mn, etc.	
I = ZnS, ZnO, SiC, SiO, etc.	
HETEROJUNCTION	AR (700 Å)
	X (1 μm)
	Cu_2O (1 to 10 μm)
X = ZnS, ZnO or SiC	

Table 2

STANDARD FREE ENERGIES FOR OXIDES AT ROOM TEMPERATURE*

Oxide	ΔG (kcal/g-mole)
MgO	-270
SiO ₂	-204
SiO	-60 to -204
MnO	-174
ZnO	-152
SnO ₂	-125
Sb ₂ O ₃	-98
Cu ₂ O	-70
CuO	-62

*These data were obtained from "Free Energy of Formation of Binary Compounds" by Thomas B. Reed, MIT (1971).

Table 3

CALCULATED CHANGE IN GIBB'S FREE ENERGY

Reaction	ΔG (kcal/g-mole)
1. $\text{Cu}_2\text{O} + \text{ZnS} \rightarrow \text{Cu}_2\text{S} + \text{ZnO}$	-12.3
2. $\text{Cu}_2\text{O} + \text{ZnS} \rightarrow \text{CuS} + \text{ZnO} + \text{Cu}$	-5.4
3. $2\text{Cu}_2\text{O} + \text{SiC} \rightarrow \text{SiO}_2 + 4\text{Cu} + \text{C}$	-98
4. $\text{Cu}_2\text{O} \rightarrow \text{CuO} + \text{Cu}$	+4.6
5. $2\text{Cu}_2\text{O} + \text{O}_2 \rightarrow 4\text{CuO}$	-25.8

Table 4
CALCULATED AM1 PHOTOCURRENT FOR Cu_2O SOLAR CELLS

Cell	J_{PH} (mA/cm ²)
Cu_2O Cell	
$S = 1, \lambda \leq 650 \text{ nm}$	17.3
$T = 1$ (Ideal AR)	
Cu_2O Cell	
$S = S_{\text{EXP}}$	10.6
$T = 1$ (Ideal AR)	
$\text{SiO} (700 \text{ \AA})/\text{Cu} (90 \text{ \AA})/\text{Cu}_2\text{O}$	
$S = S_{\text{EXP}}$	8.3
$T = T_{\text{EXP}}$	
$\text{SiO} (784 \text{ \AA})/\text{ZnS} (4 \text{ \mu m})/\text{Cu}_2\text{O}$	
$S = S_{\text{EXP}}$	10.4
$T = T_{\text{EXP}}$	

Notes:

1. S_{EXP} refers to experimental results for Cu_2O cell similar to 79FP27 in Figure 7.
2. T_{EXP} refers to calculated values for photon transmittance into Cu_2O based on measured optical constants of copper films, SiO , ZnS , and Cu_2O .

for Cu_2O . Reactions No. 4 and No. 5 are included for completeness. Note that if Cu_2O is protected from oxygen, then it will not convert to CuO .

2.2 Photocurrent of Cu_2O Solar Cells

Photocurrents of Cu_2O cells have been analyzed in great detail. Analytical studies involve determining transmittance vs wavelength through multi-layered cell structures and then calculating photocurrent utilizing experimental results for the intrinsic photoresponse S_λ . Experimental studies of photocurrent in Cu_2O cells have been conducted with $\text{Cu}/\text{Cu}_2\text{O}$ Schottky barrier cells. Optical constants have been measured for copper films as a function of film thickness. Copper film properties were then utilized in computer analyses to determine optimum values for AR coatings such that the cell photocurrent is maximized.

Calculated photocurrents are given in Table 4. The first case gives the maximum AM1 photocurrent achievable with Cu_2O , namely, 17.3 mA/cm^2 . The intrinsic photoresponse is assumed to be 1.0 for $\lambda \leq 650 \text{ nm}$, and an ideal AR coating is assumed. The calculated photocurrent for the second case is based upon experimental results for S , but still assumes an ideal AR coating. Thus, 10.6 mA/cm^2 is the limiting value for current technology Cu_2O . However, further improvement in intrinsic photoresponse will lead to larger limiting values of J_{PH} . The third case considered in Table 4 refers to an optimized $\text{Cu}/\text{Cu}_2\text{O}$ Schottky barrier structured using SiO for an AR material. $\text{Cu}/\text{Cu}_2\text{O}$ cells are being studied in detail to test photocurrent analysis techniques. As indicated, $J_{\text{PH}} = 8.3 \text{ mA/cm}^2$ is the maximum value expected for these devices. A value of 7.4 mA/cm^2 has been achieved. Finally, the fourth case refers to a $\text{ZnS}/\text{Cu}_2\text{O}$ heterojunction. Experimentally determined values of S and T are utilized in the calculation. By choosing an optimum value for SiO thickness, a value of 10.4 mA/cm^2 is predicted. The achievement of this value of photocurrent is tentatively set as an objective of this program.

3. Cu₂O FILMS

An element of this program consists of investigating approaches to fabrication of thin films of Cu₂O. Two approaches which will be studied during the next three quarters are: (1) oxidation of copper foil; and (2) transfer of thin Cu₂O films grown on copper substrates to glass substrates. No work has been conducted concerning these two approaches to date. However, Cu₂O films were grown by two other approaches in an effort to obtain thin films for optical studies. Films were obtained by reactive sputtering and by oxidation of evaporated copper films.

3.1 Reactively Sputtered Cu₂O Films

Cu₂O films of reasonable quality were obtained by sputtering from a copper target in an oxygen atmosphere, and using a dc discharge. Sputtering parameters were:

Pressure = 35 μ m O₂
Voltage = 1 kV
Current = 240 mA
Time = 30 to 60 minutes
Target = Copper

Films deposited on quartz were p-type and exhibited sheet resistances on the order of 10^5 to 10^8 $\Omega/\square$. The vacuum system presently used for sputtering is not equipped with a thickness monitor. An optical transmission curve for a sputtered film is shown in Figure 1. Also shown are results for an oxidized copper film, and a very thin single-crystal Cu₂O sample. Note the abrupt edge exhibited by the single-crystal sample. The sputtered film is estimated to be on the order of 1500 Å thick. Analysis of transmission and reflection data taken for all the thin films as well as the single-crystal sample to determine optical absorption coefficient is difficult due to surface roughness. Further work will be done in this area.

Figure 1. Optical Transmittance vs Wavelength for Cu_2O Films and Etched Single Crystal Cu_2O .

3.2 Oxidized Copper Films on MgO and Quartz

Cu_2O films were also grown by oxidizing copper films which had been evaporated onto quartz and single crystals of MgO. Cu films are oxidized in oxygen for one to three minutes at 1000°C , and then cooled in purified Argon. The transmission curve shown in Figure 1 is typical of these samples.

4. N-TYPE SEMICONDUCTOR FILMS

N-type, large-band-gap semiconductors being considered for fabrication of heterojunction cells with Cu_2O are ZnO , ZnS , and SiC . Approaches will be developed for depositing ZnS and ZnO films by well controlled thermal evaporation, and ZnO and SiC by sputtering. Thermal evaporation of films will be accomplished with a three-source system at $\approx 10^{-8}$ torr. The deposition system will be referred to as an MBE system, although some investigators insist that true molecular beam epitaxy requires 10^{-10} torr.

Efforts this quarter have primarily consisted of modifying an existing thermal evaporation system for MBE, and investigating reactively sputtered ZnO films.

4.1 MBE System

Fixturing, feedthroughs, and other parts were purchased or fabricated during this past quarter so that an existing ion-pumped single-source evaporation system could be modified to become a three-source MBE system. Figure 2 depicts the MBE system. Three Knudsen cell furnaces coupled to a thermal controller will be utilized to grow doped ZnS and other films. The substrate carousel rotates and has eight positions for samples. A thickness transducer rests at the center of the carousel. Quartz radiant heaters will allow system bakeout up to approximately 400°C . Shutters over the three sources are designed such that one source can be utilized, or all three sources used simultaneously. This arrangement will allow us to set individual component rates before starting the actual deposition. There are, of course, also shutters to cover samples. The thickness transducer is always exposed. A cross-sectional view of the Knudsen furnaces is given in Figure 3. It is anticipated that the system will be operational by early September 1979.

4.2 Reactively Sputtered ZnO Films

Reactively sputtered ZnO films were deposited with good optical properties and reasonable electrical properties. Sputtering parameters and properties for representative conductive ZnO films are given in Table 5. Thicknesses appear to be related to sputtering time according to $\approx 1000 \text{ \AA}/\text{min}$. As indicated, films

Figure 2. Schematic Diagram of MBE System.

1. Type S Thermocouple Probe With Ta Sheath
2. .001" Ta Foil Heat Shields
3. Al_2O_3 Spacers
4. .010" W Wire in High Purity Al_2O_3
5. Replaceable Carbon Crucible
6. .020" Ta Cap With Small Orifice
7. Stainless Steel Jacket
8. .020" Wall Ta Tubing
9. .020" Ta Sheet

Figure 3. Cross-Section of Knudsen Furnace.

Table 5
SPUTTERED ZnO FILMS ON QUARTZ

Sample	Voltage and Current (mA)	Inlet Composition (Atmos.)	Pressure (μm)	Time (min)	Dopant	Heat Treatment	ρ_s ($\Omega/\square$)
5-16-79	1 kV 240 mA	11% O_2 /89% Ar	30 μm	21	--	--	4.06×10^5 (As deposited)
5-20-79	1 kV 240 mA	20% O_2 /80% N_2	35 μm	45	3% In	15 min at 500°C	1.45×10^3
5-30-79	1 kV 240 mA	2.5% O_2 /97.5% Ar	35 μm	40	5% In	15 min at 500°C	4.04×10^4
6-8-79	1 kV 240 mA	5% O_2 /95% Ar	40 μm	50	5% In	--	2.8×10^5
6-20-79	1 kV 240 mA	100% O_2	35 μm	340	5% In	20 min in $\text{N}_2 - \text{H}_2$ at 500°C	1.1×10^5
6-26-79	1 kV 250 mA	100% O_2	30 μm	60	--	5 min in $\text{N}_2 - \text{H}_2$ at 500°C	1.8×10^4

are occasionally conductive as deposited. Indium doping was achieved by placing pieces of In on the Zn target. The percentage refers to percentage of area covered.

Optical transmission curves for two films are given in Figure 4. Both films were conductive. Film 5-16-79 was conductive and exhibited the transmission characteristics shown as deposited.

Figure 4. Transmittance vs Wavelength for Sputtered ZnO Films on Quartz.

5. FABRICATION AND CHARACTERIZATION OF Cu_2O SOLAR CELLS

Solar cell studies this quarter involved efforts to improve the photo-current of Cu_2O cells, electrical characterization of $\text{Cu}/\text{Cu}_2\text{O}$ Schottky barriers, and attempts to fabricate $\text{Cu}/\text{ZnO}/\text{Cu}_2\text{O}$ MIS cells using reactively sputtered ZnO interfacial layers.

5.1 Analysis of Photocurrent from $\text{Cu}/\text{Cu}_2\text{O}$ Schottky Barriers: Determination of Internal Photoresponse

Photocurrent of $\text{Cu}/\text{Cu}_2\text{O}$ Schottky barriers has been studied in detail so that approaches can be determined for maximizing the current produced by Cu_2O cells to determine the intrinsic photoresponse S_λ .

In order to determine the optimum values for Cu film and AR coating thicknesses, optical constants were determined for Cu films as a function of film thickness. Figure 5 gives the real (N) and imaginary (K) part of the index of refraction for Cu films versus wavelength. Note the dependence of N and K on film thickness. These values for optical constants were utilized to determine photon transmittance (T) into Cu_2O for $\text{Cu}/\text{Cu}_2\text{O}$ cells with an SiO_2 AR coating. In particular, optimum values of SiO_2 thickness were determined which maximize photon transmittance at selected wavelengths. Computer codes were utilized which calculate photon transmission through multi-film systems. It was determined that SiO_2 layers chosen to maximize transmittance at 500 nm also maximizes J_{PH} for an AM1 spectrum. Figure 6 gives the calculated values for photon transmittance into Cu_2O versus wavelength for cell structures with optimized SiO_2 AR layer thicknesses, and for various Cu film thicknesses. The optimum combination appears to be a 90 Å Cu film and a 700 Å SiO_2 layer. It should be noted, however, that results given in Figure 6 refer to Cu films deposited at ≈ 10 Å/sec. Preliminary results for films deposited much more rapidly, say 40 Å/sec, suggest that improved values in transmittance can be obtained with such films.

Photoresponse for three $\text{Cu}/\text{Cu}_2\text{O}$ Schottky barriers is given in Figure 7. Calculated values of T are utilized to determine the intrinsic (or internal) photoresponse (S) from the measured absolute photoresponse Q_M . Measured AM1 short-circuit currents and values of photocurrents (corrected for effects of

Figure 5. Optical Constants of Copper Films vs Wavelength.

Figure 6. Calculated Transmittance Into Cu_2O With Optimum SiO_2 AR Coating vs Wavelength.

Figure 7. Internal Photoresponse for Cu/Cu₂O Schottky Barriers.

A

B

Scanned Laser Photoresponse of Cell 79FP25. (A) Isometric Plot.
(B) Intensity Modulated Display.

R_s) for these cells are given in Table 6. Note the difference in S vs λ for cell 79FP27 compared to the other devices. Cell 79FP27 was fabricated with undoped material, while the other cells were fabricated with doped material. Analysis of these photoresponse data is under way. However, it is clear that the difference between the two types of cells is related to changes in depletion layer width and diffusion length.

Included in Table 6 are results for a recently fabricated cell, namely, 79FP28. The values listed for J_{SC} and J_{PH} represent the best values obtained to date. This cell is being stored in argon and has exhibited very stable I-V characteristics.

Scanned laser photoresponse measurements were taken for cell 79FP25. An isometric plot of photoresponse is given in Figure 8A, while a modulated intensity display is shown in Figure 8B. The photoresponse is fairly uniform across the cell except for several "spikes" indicating enhanced photocurrent. These regions could be a result of very low reflection, or due to increased depletion-layer or base-region collection. It is significant that grain boundary recombination seems to be minimal.

5.2 Electrical Characterization of Cu/Cu₂O Cells

Current-voltage analyses have been analyzed on cells 79FP24 and 79FP25. Current voltage characteristics for cell 79FP25 are shown in Figure 9, both for "dark" conditions and under AM1 simulation. Cell area, area of illumination and results under illumination are indicated in the figure. The AM1 efficiency of 1.12% represents one of the best results obtained to date.

I_{SC} - V_{OC} data were obtained for both cells by varying illumination intensity. Data obtained at 31°C for cell 79FP25 is plotted in Figure 10. Seven data points were utilized to determine cell parameters. Results are plotted using the coarse grid in Figure 10 only for the purpose of illustration. Graphical analyses were actually accomplished using expanded scales. Cell data were also analysed with a computer code based on a 3-parameter univariant search routine. Results of computer analyses are given in Table 7.

Table 6
PHOTOCURRENTS FOR Cu/Cu₂O SCHOTTKY BARRIERS

Cell No.	No AR		Optimum AR	
	J _{SC} (mA/cm ²)	J _{PH} (mA/cm ²)	J _{SC} (mA/cm ²)	J _{PH} (mA/cm ²)
79FP24	4.92	5.08	6.41	6.93
79FP25	4.62	4.66	6.24	6.66
79FP26	4.90	5.10	6.90	7.18
79FP27	5.04	5.35	7.11	7.41

Notes:

1. Cell areas were 1.5cm² and illuminated areas were 0.712cm².
2. J_{PH} is calculated from measured values of J_{SC} according to $J_{PH} \approx (1 + \frac{R_S}{R_{SH}}) J_{SC}$.

The illuminated I-V characteristics are interpreted in terms of the following model:

$$I = I_{PH} - I_0 \left[\exp \left(\frac{V_J}{n k T} \right) - 1 \right] - \frac{V_J}{R_{SH}}$$

$$V_J = V + R_S I$$

where V_J is the voltage across the junction, and the other parameters having the usual definition. In Figure 10, $I_{SC} - V_{OC}$ data pairs are plotted in two ways. First the data pairs are plotted with no correction. If one draws a straight line through these data points to determine I_0 and n , then one is assuming that $R_S = 0$, and $R_{SH} = 0$. The fit to experimental data obtained this way is usually inadequate for Cu_2O . Assuming a finite R_S and R_{SH} , one finds that under open circuit conditions

$$I = 0 = I_{PH} - I_0 \left[\exp \left(\frac{V_{OC}}{n k T} \right) - 1 \right] - \frac{V_{OC}}{R_{SH}}$$

$$I^1 = \left(I_{PH} - \frac{V_{OC}}{R_{SH}} \right) \approx I_0 \exp \left(\frac{V_{OC}}{n k T} \right)$$

a plot of I^1 vs V_{OC} is given in Figure 10 assuming values of R_{SH} and R_S taken from the illuminated I - V curve in Figure 9 -- i.e., R_S is determined from the slope of I vs V in the forward direction, and R_{SH} from the slope of I vs V in the reverse direction. Since $R_S \neq 0$, we have estimated I_{PH} as

$$I_{PH} \approx I_{SC} \left(1 + \frac{R_S}{R_{SH}} \right)$$

The most accurate fitting of experimental data is obtained by searching over the parameters and determining which set minimizes the error between calculated and measured $I_{SC} - V_{OC}$ data. Note the improved agreement between parameters obtained graphically and those obtained by a computer analysis, when a plot of I vs V_{OC} is utilized.

The results obtained for J_0 and n for cells under illumination are approaching those expected for ideal Cu / Cu_2O Schottky barrier. The J_0 values obtained by computer analysis imply that $\phi_{BP} = 0.82$ eV. Assuming $\phi_m = 4.4$ eV for

CURRENT VOLTAGE CHARACTERISTICS OF Cu/Cu₂O SCHOTTKY BARRIER

CELL STRUCTURE

CELL 79FP25

Cu THICKNESS = 92 Å

AR COATING = 720 Å SiO

JUNCTION AREA = 1.5 cm²

AMI PERFORMANCE

AMBIENT TEMP

ILLUM AREA = 0.71 cm²

$J_{sc} = 6.24 \frac{\text{mA}}{\text{cm}^2}$

$V_{oc} = .302 \text{ V.}$

FF = 0.59

EFF = 1.12%

Figure 9. Current-Voltage Characteristics for Cu/Cu₂O Schottky Barrier.

$I_{SC} - V_{OC}$ ANALYSIS FOR CELL 79FP25

Figure 10. $\log I_{SC}$ vs V_{OC} Plot for Cell Cu/Cu₂O Schottky Barrier 27FP25.

TABLE 7

I-V Parameters for Cu/Cu₂O Schottky Barriers
 Obtained With Computer Analysis of $I_{SC} - V_{OC}$
 Data

	CELL 79F24	CELL 79FP25
Temperature	35°C	33°C
J_0 (A/cm ²)	8.57×10^{-6}	2.18×10^{-7}
n	1.55	1.07
R_S (Ω)	0.84	6.83
R_{SH} (Ω)	199	657
Average Absolute Percent Error	0.28%	.054%

copper, and $\chi = 3.2$ eV and $E_g = 2.0$ eV for Cu_2O , the expected value for ϕ_{BP} is 0.8 eV.

Further analyses of $I_{\text{SC}} - V_{\text{OC}}$ data will be done for various temperatures to determine if what appears to be shunt resistance effects are actually tunnelling current mechanisms.

5.3 Cu/ZnO/Cu₂O MIS Cells

MIS structures were made by using reactively sputtered ZnO interfacial layers. An open circuit voltage of 0.42 volts was obtained in one case. It appears that current methods for sputtering are inadequate for depositing ZnO as an interfacial layer in a MIS structure. The present arrangement for sputtering was assembled rather quickly for preliminary experiments. A shutter is needed and the sample presently is probably bombarded with negative ions and neutral atoms since it is the positive electrode. An improved system will include a shutter and the use of an ion gun.

6. FUTURE WORK

During the next quarter, it is expected that our MBE system will be operational. New fixturing for reactive sputtering will also be available. Efforts will concentrate on the following tasks:

1. Increased emphasis on investigation of current mechanisms in Cu_2O cells;
2. Increased Cu_2O cell photocurrent analysis;
3. MBE deposition of ZnS films;
4. Development of an approach for Cu_2O film transfer from partially oxidized copper substrates;
5. Fabrication and characterization of $\text{M}/\text{SiO}_x/\text{Cu}_2\text{O}$ MIS cells and $\text{ZnX}/\text{Cu}_2\text{O}$ heterojunctions ($X = \text{O}$ and S).

APPENDIX A
RESEARCH CONTRIBUTORS

Principal Investigator

Dr. Larry C. Olsen

Senior Research Engineer

Dr. F. W. Addis

Research Engineers

Donald L. Barton, M.S. Electrical Engineering

Robert C. Bohara, M.S. Materials Science

Frank Ladd, B.S. Physics

Graduate Research Assistants

Wesley Miller, Ph.D. Candidate in Materials Science

Dale Tarrant, M.S. Candidate in Materials Science

Joseph Burdick, M.S. Candidate in Materials Science