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**METAL-INSULATOR-SEMICONDUCTOR
PHOTOVOLTAIC DEVICES**

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METAL-INSULATOR-SEMICONDUCTOR PHOTOVOLTAICS

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TASK DESCRIPTION:

The overall objective of this program is to conduct research on metal-insulator-semiconductor (MIS) solar cells to improve understanding of the basic parameters which control photovoltaic processes in these cell structures. Current work includes fabrication, characterization, and theoretical studies of single crystal silicon-based cells, with SiO_x as the insulating film and Al or Au as the front metal contact. Studies of these two systems are intended to provide needed reference systems from which improved single crystal or polycrystalline devices can be systematically developed.

The approach to cell fabrication involves growth of a SiO_x layer on a silicon substrate, and subsequent evaporation of a metal layer for the front contact by vacuum evaporation or electron beam deposition. Characterization of cells involves both physical and electro-optical measurements. Scanning Auger electron spectroscopy (AES) and secondary ion mass spectroscopy (SIMS) are utilized to determine depth concentration profiles and the nature of bonding in the interfacial region. Electro-optical measurements include current-voltage, capacitance-voltage, and spectral photoresponse measurements with the completed cell. In addition, ellipsometric measurements are utilized to determine oxide film thickness and the optical parameters for metal films on silicon. These results are compared to parameters determined from reflection and transmission measurements made on films deposited on quartz.

Results of physical and electro-optical characterization are correlated with theoretical models for MIS cells.

RECENT PUBLICATIONS:

- R. P. Turcotte, L. C. Olsen, and D. L. Barton, "Al/SiO₂ and Au/SiO₂/Si Photovoltaic Cells," presented at the American Ceramic Society meeting, Detroit, May 1978.
- L. C. Olsen and R. P. Turcotte, "Metal-Insulator-Semiconductor Photovoltaics," presented at the DOE Photovoltaics Branch Silicon Projects meeting, May 4-5, 1978.
- L. C. Olsen, D. L. Barton, and R. P. Turcotte, "Physical Structure and Photovoltaic Properties of Al/Si Solar Cells," submitted for publication to Appl. Phys. Letters.

TECHNICAL PROGRESS IN FY 1979:

Cell studies have involved both Al/SiO_x/Si and Au/SiO_x/Si solar cells. Most of this year's effort has been developed to the Al-Si device studies. Significant progress was made in determining the physical structure of both types of cells, and towards developing a high efficiency Al-Si cell. Development of an efficient cell was achieved by establishing improved fabrication procedures and by achieving a significant improvement in photon transmission through the Al film to the p-Si substrate. All cells were fabricated on float-zone single-crystal silicon with the resistivity being in the range of 1 to 5 Ω -cm. Two-inch wafers polished on one side are scribed and broken into 1.5 cm x 1.5 cm squares. Cell fabrication involves the following steps: wafers are cleaned and etched with a standard procedure; a back contact is deposited; an oxide interfacial layer is grown on the front surface; front metal film is deposited; AR coatings deposited.

Auger analyses of a large number of Al/SiO_x/Si devices demonstrated a high degree of reproducibility in terms of film thicknesses achieved and a lack of impurities (e.g., carbon) sometimes found in early devices. A very good correlation of film thickness (by ellipsometry) and integrated oxygen concentration in the insulating film region has been demonstrated which gives some credibility to both measurements. We point this out since at the film thicknesses of interest (5-100 Å), the interpretation of either ellipsometry data or Auger profiles is not entirely unambiguous.

Perhaps the most significant finding reached this year in the Al/SiO_x/Si system is that the insulating film is not silicon oxide at all, but that most of the oxygen present in the interfacial region is bonded to aluminum, as shown by both energy shifts of the Auger spectra, and by changes of intensity of some Auger peaks, both related to the degree of oxide/metal character present. Although thermodynamic considerations, in fact, suggest Al₂O₃ will form at the expense of SiO₂, we are not aware of any previous suggestions or experimental evidence that this occurs. Since previous theoretical models assume simple SiO₂ or SiO_x insulating films in these systems, our results are quite significant.

A second finding has been that the width of the insulating region in a completed device does not appear to be directly related to the thickness of the thermally grown oxide film (5-50 Å) present before Al deposition.

In the Auger profiles, the sputtering time required to traverse the oxygen containing region does not change significantly, although a regular increase in the oxygen concentration is observed. Some additional work is required to understand this behavior.

Data on the Au/SiO_x/Si system are less complete but the film boundaries are much sharper than in the Al cells. As expected, oxygen is bound to Si in these devices.

Electro-optical investigations of Al-Si and Au-Si solar cells have included determination of optical properties of metal films, current-voltage and capacitance measurements, and solar cell efficiency determination. The index of refraction and absorption coefficient is obtained for metal films deposited on quartz by measuring reflection and transmission versus wavelength. This information can then be utilized to calculate photon transmission into the silicon region of an Al-Si or Au-Si cell. In order to determine an optimum cell structure, sheet resistance was measured for metal films as a function of film thickness and deposition rate. For example, it was determined that deposition rates greater than 10 Å/sec are required for Al films to be adequately conductive. Furthermore, photon transmission through Al films on the order of 100 Å is only 10%. Thus, to optimize the Al/SiO_x/Si cell, we are utilizing 50 Å Al films deposited at a rate on the order of 10 Å/sec.

Computer codes were developed with which photon transmission through an Al-Si cell with any number of AR coatings can be calculated. A detailed optimization of the Al-Si cell will be done in FY 1980. However, preliminary studies have led to a structure consisting of SiO(600 Å)/Al(50 Å)/SiO(15 Å)/pSi. The SiO₂ thickness refers to a thickness indicated by ellipsometry. Several cells with AMI efficiencies greater than 7% were obtained. The best photo-voltaic parameters achieved to date are: short-circuit current of 24.8 mA/cm²; open-circuit voltage of 0.525 V; fill-factor of 0.74; and AMI efficiency of 7.83%. Even with thin Al coatings and an AR coating, the total photon transmission into silicon is only 60%. It is expected that further optimization will increase transmission to 90%. Results obtained to date compare very favorably with other leading DOE programs concerning MIS cell studies.

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Poster Session Figures

MIS SOLAR CELLS - INTRODUCTION

OVERALL OBJECTIVE

- TO INVESTIGATE METAL - INSULATOR - SEMICONDUCTOR DEVICES TO IMPROVE UNDERSTANDING OF THE BASIC PARAMETERS WHICH CONTROL THE PHOTOVOLTAIC PROCESSES IN SUCH CELLS

APPROACH

- INVESTIGATE MIS CELLS BASED ON SINGLE CRYSTAL SILICON TO ESTABLISH A REFERENCE SYSTEM. INITIAL EFFORTS ARE BEING DEVOTED TO $\text{Au/SiO}_x/\text{nSi}$ AND $\text{Al/SiO}_x/\text{pSi}$ CELLS
- UTILIZE SURFACE ANALYSIS TECHNIQUES AND ELLIPSOMETRY TO CHARACTERIZE THE PHYSICAL STRUCTURE OF MIS CELLS
- CARRY OUT ELECTRO-OPTICAL CHARACTERIZATION INCLUDING: PHOTORESPONSE, I-V, C-V, C- ω AND SOLAR CELL EFFICIENCY MEASUREMENTS
- CONTINUALLY REFINE THEORETICAL MODELS TO ASSIST IN INTERPRETING AND GUIDING EXPERIMENTAL STUDIES
- EMPHASIZE CORRELATION OF ELECTRO-OPTICAL PROPERTIES WITH PHYSICAL STRUCTURE

PHYSICAL AND ELECTRONIC STRUCTURE OF MIS SOLAR CELL

(A) LAYERED STRUCTURE

(b) ELECTRON ENERGY BAND DIAGRAM

FILM GROWTH IN O₂ AT HIGH TEMPERATURE

FILM GROWTH IN AIR ($\sim 25^{\circ}\text{C}$) AFTER CLEANING AND HF ETCH

AUGER INTEGRATED OXYGEN CONCENTRATION VERSUS ELLIPSOMETER THICKNESS FOR SiO_2 FILMS ON Si

**AUGER DEPTH PROFILE:
Au-Si CELL WITH THICK OXIDE LAYER**

Si AUGER ELECTRON ENERGY AND INTENSITY RATIO VERSUS SPUTTER TIME

AUGER DEPTH PROFILE: Au-Si CELL WITH THIN OXIDE LAYER

Si AUGER ELECTRON ENERGY AND INTENSITY RATIO VERSUS SPUTTER TIME

AUGER DEPTH PROFILE: Al-Si CELL WITH THICK OXIDE LAYER

AUGER DEPTH PROFILE: Al-Si CELL WITH THIN OXIDE LAYER

SHEET RESISTANCE VERSUS ALUMINUM FILM THICKNESS

APPROACH TO MEASUREMENT OF OPTICAL CONSTANTS FOR METAL FILMS ON SILICON

- DEPOSIT METAL FILM SIMULTANEOUSLY ON SILICON AND QUARTZ
- MEASURE REFLECTION, $R(N,K)$, AND TRANSMITTANCE, $T(N,K)$, FOR FILM ON QUARTZ WITNESS
- UTILIZE COMPUTER ANALYSIS TO DETERMINE N AND K FOR METAL FILM
- CALCULATE R AND T FOR FILM ON SILICON
- COMPARE CALCULATED AND MEASURED R VERSUS λ FOR FILM ON SILICON

OPTICAL CONSTANTS FOR VARIOUS THICKNESS OF ALUMINUM

REFLECTION FROM 90 Å Al ON Si

TRANSMITTANCE INTO SILICON WITH OPTIMUM SiO AR COATING

REFLECTION FROM Al/Si CELL

PHOTORESPONSE FOR Al/Si CELL

Al-Si MIS SOLAR CELL PERFORMANCE

CELL STRUCTURE

49 Å Al

~12 Å SiO_x

CELL AREA = 1.5 cm²

FABRICATION

SiO_x GROWN @ 500°C

SOLAR SIMULATION

100 mW/cm² ELH BULB
ILLUMINATION

ILLUMINATED AREA = 0.705 cm²

PERFORMANCE

	J _{PH} (mA/cm ²)	V _{OC} VOLTS	FF	EFF (%)
WITHOUT AR	15.6	0.495	0.66	5.1
WITH AR	24.8	0.495	0.64	7.8

KEY RESULTS TO DATE

- **TENTATIVE MODEL FOR PHYSICAL STRUCTURE OF Al-Si MIS CELLS ESTABLISHED.**
- **ELECTRICAL AND OPTICAL PROPERTIES OF ALUMINUM FILMS DETERMINED**
- **OPTIMUM AR COATING DETERMINED FOR Al-Si CELLS. ACHIEVED PHOTOCURRENT OF 28 mA/cm².**
- **AMI EFFICIENCY OF 7.8% ACHIEVED WITH Al/Si CELL.**
- **INSULATING FILM IN Al/SiO_x/Si SYSTEM IS *NOT* SiO₂. MOST OF THE OXYGEN PRESENT IN INTERFACIAL REGION IS BONDED TO Al.**
- **WIDTH OF INSULATING REGION IN A COMPLETED DEVICE DOES *NOT* APPEAR TO BE DIRECTLY RELATED TO THE THICKNESS OF THE THERMALLY GROWN OXIDE FILM (5-50 Å) PRESENT BEFORE Al DEPOSITION.**

FUTURE RESEARCH

- **DETERMINATION OF PHYSICAL STRUCTURE OF Al-Si MIS CELLS.**
- **DEVELOPMENT OF APPROACH TO MEASURING OPTICAL PARAMETERS OF LAYERED STRUCTURES WITH ELLIPSOMETRY.**
- **EFFECT OF AR DEPOSITION ON CELL PHYSICAL STRUCTURE.**
- **INVESTIGATION OF Al-Si CELL PERFORMANCE AS SiO_2 THICKNESS IS VARIED.**
- **OPTIMIZATION OF Al-Si MIS STRUCTURE (EFFICIENCY $>10\%$).**
- **DEVELOPMENT OF AN U.H.V. SYSTEM WITH IN-SITU ELLIPSOMETRIC, ION CLEANING AND DEPOSITION CAPABILITIES.**
- **FURTHER INVESTIGATION OF THE $\text{Au}/\text{SiO}_2/\text{Si}$ SYSTEM.**