N76 12494

APPLIED RESEARCH ON II-VI COMPOUND MATERIALS FOR HETEROJUNCTION SOLAR CELLS

NSF Grant GI-38445X

July 1, 1974 - June 30, 1975

$ 53,954

Richard H. Bube

Department of Materials Science and Engineering
Stanford University
Stanford, California 94305

Professor Richard H. Bube, Principal Investigator

National Solar Photovoltaic Program Review Meeting
July 22-25, 1975
Los Angeles, California

ABSTRACT

The objective of this grant is the investigation of heterojunction solar cells based on several II-VI compound systems suitable for large-scale terrestrial utilization.

Several II-VI heterojunctions show promise for photovoltaic conversion of solar energy. The three of greatest interest are p-CdTe/n-CdS, p-CdTe/n-ZnSe, and p-ZnTe/n-CdSe. The last of these three is of interest primarily as an opportunity to determine the effects of very small lattice mismatch rather than as an actual solar cell. p-CdTe/n-CdS heterojunction cells have been prepared by close-spaced transport deposition of p-CdTe on single crystal n-CdS, and by two-source vacuum evaporation of n-CdS on single crystal p-CdTe. Both types of cells, in an experimen′ l stage, are quite comparable, exhibiting values of quantum efficiency between 0.5 and 0.9, open-circuit voltages between 0.50 and 0.66 V, fill factors between 0.4 and 0.6, and solar efficiencies up to 4 percent. Cells of p-ZnTe/n-CdSe have also been made by close-spaced vapor transport deposition of n-CdSe on single crystal p-ZnTe.

A detailed program of heterojunction evaluation has been initiated, involving (1) J-V characteristics in the dark vs temperature to determine diode properties in the absence of illumination, (2) J-V characteristics in the light using the solar simulator, (3) V_{oc} vs ln J_{sc} as a function of light intensity at different temperatures to determine magnitudes and temperature dependence of key diode parameters, (4) junction capacitance vs voltage in light and dark, (5) SEM determination of minority carrier diffusion lengths, (6) optical transmission to determine exact variation of absorption constant with photon energy, and (7) spectral response of J_{sc} to determine dependence of quantum efficiency on photon energy.

Measurement of J-V curves in the dark as a function of temperature for evaporated n-CdS on p-CdTe heterojunctions reveals two ranges of behavior: above 250°K, the current is thermally activated, $\gamma = 2.4$ and is independent of temperature, and $J_o = 1.9 \times 10^2 \exp(-0.54\ eV/kT)\ A/cm^2$; below 250°K, tunneling dominates, $\alpha = 21\ V^{-1}$ and is independent of temperature, and $J_o = 5.7 \times 10^{-10}\ A/cm^2$ independent of temperature. J_o and/or γ may be light-dependent, as evidenced by the crossover of light and dark J-V curves. Low fill factors may be associated with a bias-dependent quantum efficiency. No transient or quenching effects have been observed in this system at room temperature.

Making ohmic, low-resistance contacts to p-CdTe has been a major problem. Such contacts can be made with Ni to a surface etched with $K_2Cr_2O_7{:}H_2SO_4{:}H_2O$, after heat treatment, if the CdTe resistivity is less than 10 ohm-cm. Ohmic, low-resistance contacts have been made with Ni to 133 ohm-cm p-CdTe after implantation of the CdTe with As. Evidence is conclusive from a variety of sources that the contact consists of a thin Schottky barrier with current transport dominated by tunneling.

p-ZnTe/n-CdSe heterojunctions show quantum efficiencies between 0.18 and 0.30, open-circuit voltages between 0.55 and 0.68 V, fill factors between 0.38 and 0.49, and solar efficiencies up to about 1 percent. A bias-dependent quantum efficiency is indicated due to short diffusion length of photoexcited holes in CdSe. V_{oc} vs ln J_{sc} measurements indicate that between 74°C and 221°C α changes from 10.2 to 15.6 V^{-1} (γ from 3.25 to 1.49) and $J_o = 1.3 \times 10^{-3} \exp(-0.33\ eV/kT)$, suggesting thermally assisted tunneling as the current transport mode.

Future work includes detailed correlation of diode parameters in p-CdTe/n-CdS and p-ZnTe/n-CdSe with preparation variables, investigation of methods to increase the conductivity of both surface and bulk p-CdTe, determination of the properties of p-ZnTe/n-CdSe junctions made on (111) oriented ZnTe to achieve minimum lattice mismatch condition, and evaluation of p-CdTe/n-ZnSe heterojunctions.

APPLIED RESEARCH ON II-VI COMPOUND MATERIALS FOR HETEROJUNCTION SOLAR CELLS
NSF Grant GI-38445X

Stanford University

July 1, 1974 - June 30, 1975

$ 53,954

Professor Richard H. Bube
Principal Investigator

PROJECT OBJECTIVES

INVESTIGATION OF HETEROJUNCTION SOLAR CELLS BASED ON SEVERAL II-VI COMPOUND SYSTEMS SUITABLE FOR LARGE-SCALE TERRESTRIAL UTILIZATION.

PLANNED ACTIVITY LAST 6 MONTHS

* PREPARE AND INVESTIGATE ALL FILM p-CdTe/n-CdS CELLS
* OPTIMIZE ELECTRICAL CONTACTS TO p-CdTe
* BRING NEW VACUUM SYSTEM TO FULL OPERATING POTENTIAL
* BEGIN EVALUATION OF OTHER II-VI HETEROJUNCTION SYSTEMS:
  p-ZnTe/n-CdSe, p-CdTe/n-ZnSe, p-ZnTe/n-CdTe

HETEROJUNCTION EVALUATION

* J-V CHARACTERISTICS IN DARK vs TEMPERATURE
  Diode properties in absence of illumina:ion

* J-V CHARACTERISTICS IN LIGHT
  Using so: r simulator, determine J_{sc}, V_{oc}, fill fa^tor, collection efficiency, solar efficiency

* V_{oc} vs ln J_{sc} PLOTS AS A FUNCTION OF LIGHT INTENSITY AT DIFFERENT TEMPERATURES
  Diode constant at different tempera.ures, $J_o(T)$, and effective barrier height for forward currents in light

* JUNCTION CAPACITANCE vs V IN DARK AND LIGHT
  Width and variation of depletion layer

* SEM DETERMINATION OF MINORITY CARRIER DIFFUSION LENGTHS

* OPTICAL TRANSMISSION
  Absorption constant vs photon energy

* SPECTRAL RESPONSE OF J_{sc}
  Variation of quantum efficiency on phc .cn energy

EVAPORATED n-CdS ON SINGLE CRYSTAL p-CdTe

* HEAT TREATMENT TO ABOUT 430°C REQUIRED FOR OPTIMUM PERFORMANCE

* DIODE CHARACTERISTICS IN THE DARK vs TEMPERATURE

$T > 250°K \qquad J = J_o \left[\exp\left(qV/\eta kT\right) - 1\right]$

$J_o = J_o^o \exp\left(-E^*/kT\right)$

$\eta = 2.4 \qquad E^* = 0.54$ eV

$T < 250°K \qquad J = J_o \left[\exp(\alpha V) - 1\right]$

$J_o = 5.7 \times 10^{-10}$ A/cm²

$\alpha = 21\ V^{-1}$

* J_o AND/OR η ARE LIGHT DEPENDENT AS EVIDENCED BY THE CROSSOVER OF LIGHT AND DARK J-V CURVES

* A BIAS-DEPENDENT COLLECTION EFFICIENCY MAY CONTRIBUTE TO LOW FILL FACTORS

* NO TRANSIENT OR QUENCHING EFFECTS OBSERVED AT ROOM TEMPERATURE

<u>ELECTRICAL CONTACTS TO p-CdTe</u>

* OHMIC, LOW-RESISTIVITY CONTACT TO SURFACE OF p-CdTe ETCHED WITH $K_2Cr_2O_7:H_2SO_4:H_2O$ FOR RESISTIVITY $\lessdot$ 10 OHM-CM

* OHMIC, LOW-RESISTIVITY CONTACT TO SURFACE OF p-CdTe IMPLANTED WITH As FOR RESISTIVITY OF 133 OHM-CM

* DEVELOPMENT OF A "3-POINT" MEASURING TECHNIQUE THAT ALLOWS CELL EVALUATION EVEN IF CONTACTS NOT IDEAL

* EVALUATION OF OHMIC TO NON-OHMIC TRANSITION BY MEASURING CONTACT PROPERTIES vs TEMPERATURE

* MODEL FOR CONTACT INVOLVING A THIN SCHOTTKY BARRIER WITH CURRENT TRANSPORT DOMINATED BY TUNNELING
    Chemical effect of etching
    Auger analysis of contact
    Low-temperature capacitance
    Quantitative shape of temperature dependence

OTHER II-VI SYSTEMS: p-ZnTe/n-CdSe

* 11 HETEROJUNCTIONS MADE BY CLOSE-SPACE VAPOR TRANSPORT OF CdSe ONTO SINGLE CRYSTAL ZnTe
* OHMIC LOW-RESISTANCE CONTACTS POSSIBLE TO ETCHED p-ZnTe
* TYPICAL CELL PARAMETERS

V_{oc}	0.55 - 0.68 V	Fill Factor	0.38 - 0.49
Quantum Efficiency	0.18 - 0.30	Solar Efficiency	0.55 - 0.85 percent

* DIODE CHARACTERISTICS AT 22°C

  $\eta_{dark} = 2.38$ $\eta_{light} = 2.41$

  $J_o dark = 4.2x10^{-9}$ A/cm² $J_o light = 1.2x10^{-8}$ A/cm²

* TEMPERATURE DEPENDENCE OF DIODE CHARACTERISTICS IN LIGHT

  η at 74°C = 3.25 η at 221°C = 1.49

  $J_o = 1.3 \times 10^{-3} \exp(-0.33\ eV/kT)$ A/cm²

SUMMARY OF KEY RESULTS

* CONTACTS TO p-CdTe ARE UNDERSTOOD; OHMIC, LOW-RESISTANCE CONTACTS CAN BE MADE; CELLS CAN BE EVALUATED EVEN IN THE ABSENCE OF IDEAL CONTACTS

* TWO MECHANISMS DETECTED FOR J_o for p-CdTe/n-CdS: HIGH-TEMPERATURE THERMALLY ACTIVATED WITH $E^* = 0.54$ eV, AND LOW-TEMPERATURE TUNNELING

* J_o for p-ZnTe/n-CdSe IS THERMALLY ACTIVATED AT HIGH TEMPERATURES WITH $E^* = 0.33$ eV

* EVIDENCE FOR A BIAS-DEPENDENT COLLECTION EFFICIENCY CONTRIBUTING TO POOR FILL FACTORS

* DEVELOPMENT OF VACUUM EVAPORATOR SYSTEM

* IMPORTANCE OF LIGHT AND PREPARATION VARIABLES ON J_o and η

PLANNED ACTIVITY FOR NEXT 6 MONTHS

* p-CdTe/n-CdS HETEROJUNCTIONS

- Correlation of E* with preparation variables
- Determine presence and extent of bias-dependent collection efficiency
- Transient measurements at low T to determine effect of light on J_o and
- Optimization of CdS film deposition

* ELECTRICAL CONTACTS TO p-CdTe

- Evaluations for other metals with different work functions
- Investigation of methods to make surface high conductivity
- Contacts to p-CdTe films

* p-ZnTe/n-CdSe HETEROJUNCTIONS

- Properties of junctions on (111) oriented ZnTe to achieve minimum lattice mismatch (0.35 percent)
- Full characterization of junction properties

* OTHER SYSTEMS

- The system of principal interest is p-CdTe/n-ZnSe
  - Larger "window"
  - Larger diffusion voltage
  - Susceptible of extension to p-CdZnTe/n-ZnSSe
- If results with p-CdTe/n-CdS warrant, then p-CdTe/n-CdZnS