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THI~~S~~N FILM CADMIUM TELLURIDE SOLAR CELLS

Technical Progress Report No. 1 for July 1—September 30, 1979

By
Ting L. Chu

October 1979

Work Performed Under Contract No. AC04-79ET23009

Southern Methodist University
Dallas, Texas

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U.S. Department of Energy

Solar Energy

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Summary

This is the First Technical Progress Report of a research program "Thin Films Cadmium Telluride Solar Cells" supported by the U. S. Department of Energy under Contract No. DE-AC04-79ET23009. The objectives of this contract are to investigate thin films of cadmium telluride on low cost substrates and to demonstrate the feasibility of producing thin film cells with a conversion efficiency of 10% or higher.

Efforts during the first quarter have been directed to the construction of apparatus for the chemical vapor deposition of cadmium telluride films, the selection and preparation of substrates, and the deposition and characterization of cadmium telluride films. Cadmium telluride films have been deposited on a number of substrates by the direct combination of cadmium and tellurium on the substrate surface at 550°-740°C. At substrate temperatures below 550°C, the deposit is non-adherent. In the temperature range 580°-740°C, the deposition rate is 0.5-1 μm/min, and the microstructure and crystallographic properties of deposited films have been investigated. Without intentional doping, cadmium telluride films deposited on mullite substrates have room temperature resistivities and carrier concentrations of $(4-7) \times 10^{4}$ ohm-cm and $(6-9) \times 10^{12}$ cm^{-3}, respectively.

Current-voltage measurements of Schottky barriers prepared from cadmium telluride films indicate the rectifying interface in CdTe/W/graphite, CdTe/graphite, CdTe/Al/graphite structures and the presence of pinholes in the films. The use of an indium interlayer has reduced considerably both the interface resistance and pinhole density. Further work will be directed to the measurement of interface resistance and the doping of cadmium telluride films.

I. Introduction

This is the First Technical Progress Report of a research program "Thin Films Cadmium Telluride Solar Cells" supported by the Department of Energy under Contract No. DE-AC04-79ET23009. The objectives of this contract are (1) to conduct research and development of thin film cadmium telluride solar cells on low-cost substrates, and (2) to demonstrate the feasibility of producing thin film cells with a conversion efficiency of 10% or higher.

Cadmium telluride, a direct gap semiconductor with a room temperature band gap energy of 1.50 eV, is a promising thin film photovoltaic material. Its solar cells have a higher theoretical conversion efficiency than silicon and gallium arsenide cells.(1) Because of its sharp optical absorption edge and large absorption coefficients, solar radiation with energy in excess of the energy gap is essentially all absorbed within a few micrometers of the surface, and a relatively short minority carrier diffusion length in the material can be tolerated. The deposition of cadmium telluride films on foreign substrates and the preparation of cadmium telluride solar cells have been under investigation for many years. The material and device work relevant to this program are briefly reviewed below.

I. 1 Properties of Cadmium Telluride

Cadmium telluride crystallizes in the zincblende structure, and its room temperature lattice parameter, density, thermal expansion coefficient, melting point, room temperature electron mobility, room temperature hole mobility, and refractive index are 6.48 Å, 5.86 g cm^{-3}, 5.5 x 10^{-6} $^{o}C^{-1}$, 1098°C, 1050 cm^2/V-sec, 80 cm^2/V-sec, and 2.8, respectively. The preparation and processing of cadmium telluride requires a detailed knowledge of the pressure, temperature, and composition relations in the cadmium-tellurium system. The temperature-composition relation of the cadmium-tellurium system is well established and is reproduced in Figure 1.(2) It has a maximum melting point of 1092° ± 1°C at the stoichiometric composition, an eutectic

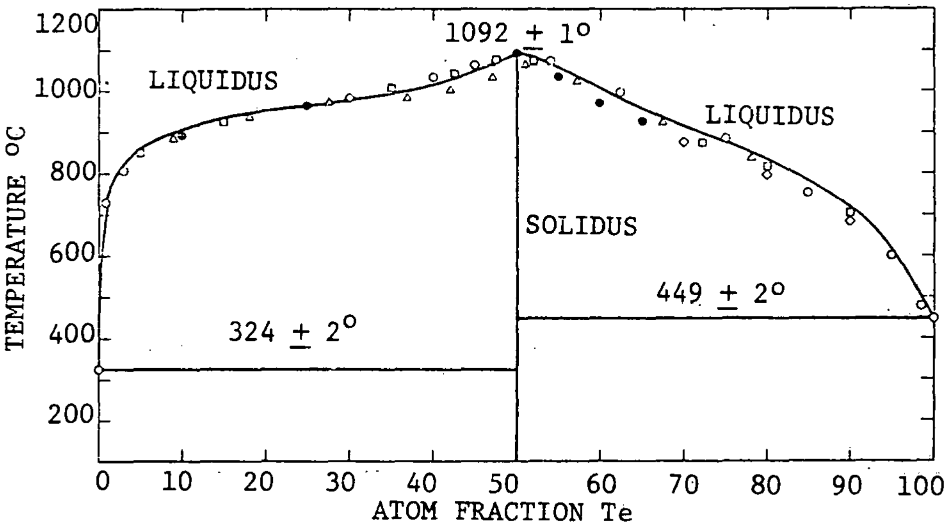


Figure 1 Temperature-composition relation for the cadmium-tellurium system.

temperature of 324° ± 2° on the cadmium-rich side, and an eutectic temperature of 449° ± 2°C on the tellurium-rich side (about 99% tellurium). The homogeneity region of cadmium telluride may be as high as 1% (atomic) on both the cadmium-rich and tellurium-rich sides of the stoichiometric composition. However, the concentration of electrically active centers is considerably less, as shown in Fig. 2.

At high temperatures, cadmium telluride dissociates into the elements according to the following equation (no CdTe molecules have been detected in the gas phase):

$$2\ CdTe(s) \rightleftarrows 2\ Cd(g) + Te_2(g)$$

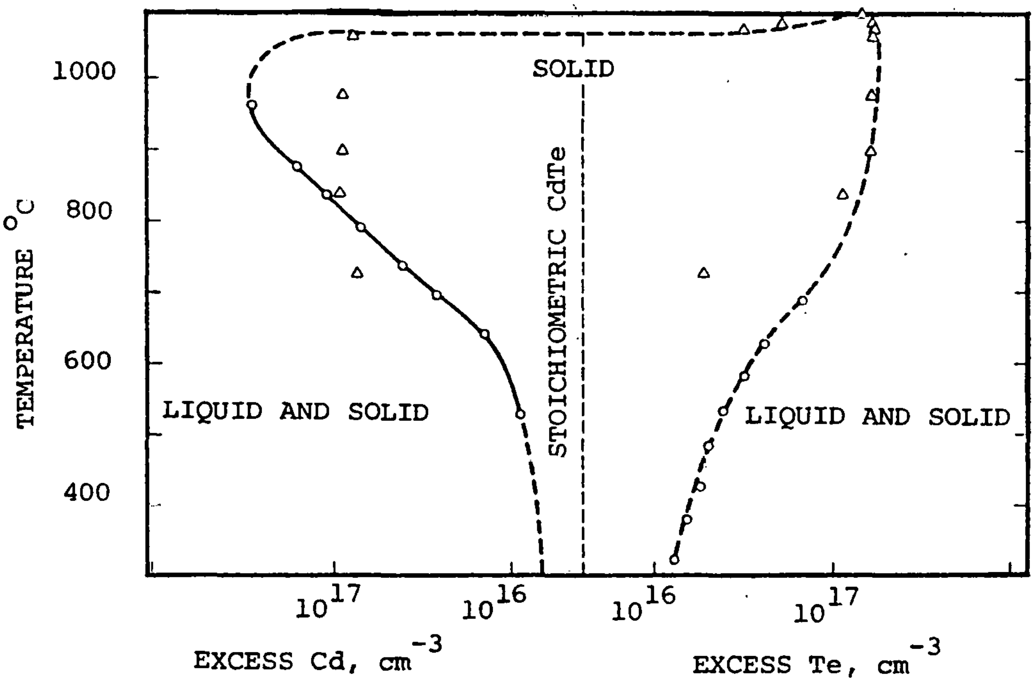


Figure 2 Temperature-composition relation showing the extent of the electrically active homogeneity region in cadmium telluride.

The partial pressure of cadmium is twice the partial pressure of tellurium, and the partial pressure of tellurium may be approximated by:

$$\log p_{Te_2}\ (\text{atm}) = 6.346 - (10000/T)$$

The dissociation pressure of cadmium telluride in the temperature range 700° - 1000° K is shown in Fig. 3, where the vapor pressures of elemental cadmium and tellurium are also shown for comparison. Thus, during the high temperature deposition and processing of cadmium telluride, an external pressure of cadmium or tellurium must be used to suppress the decomposition of cadmium telluride.

I. 2 Vapor Deposition of Cadmium Telluride Films

The deposition of cadmium telluride films has been carried out by

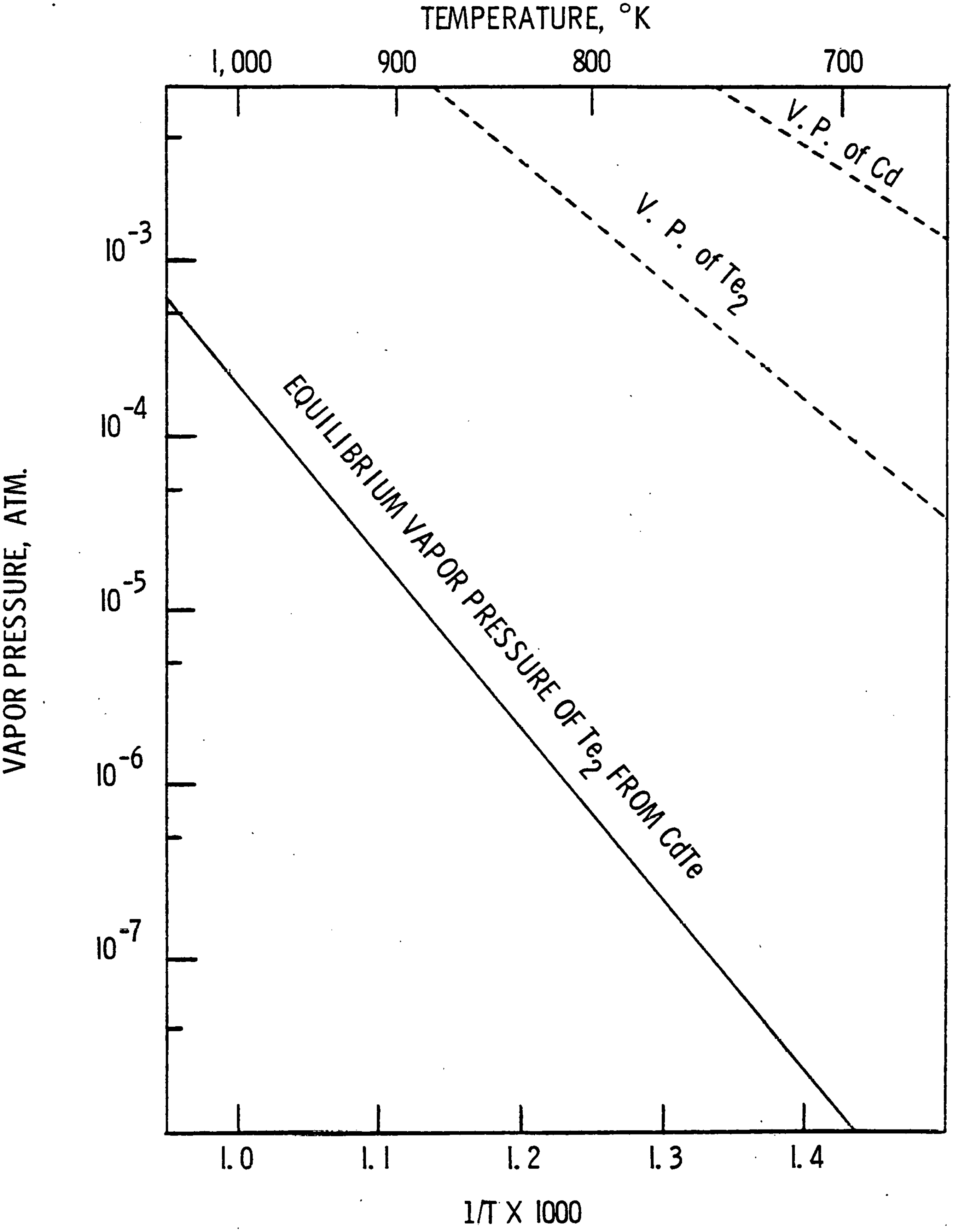


Fig. 3 The equilibrium vapor pressure of tellurium from the dissociation of cadmium telluride and the vapor pressures of elemental cadmium and tellurium in the temperature range 700°-1000°K.

vacuum evaporation, sublimation in an inert atmosphere, chemical transport, and electrolytic techniques.

In the vacuum evaporation technique, cadmium telluride or the constituents may be used as the source material; the nature of the substrate, the substrate temperature, and deposition rate are the most important parameters affecting the properties of deposited films. The growth of films of cadmium chalcogenides on single crystalline foreign substrates, such as sodium chloride, potassium chloride, mica, germanium, silicon, etc. has been extensively reviewed; epitaxial films of both zincblende and wurtzite structures have been obtained at substrate temperatures up to 500°C.(3) When glass is used as a substrate,(4) stoichiometric crystalline films with zincblende structure has been obtained. To avoid condensation of free tellurium, substrate temperatures above 150°C are required, and the grain size depends strongly on substrate temperature. At 150°C, films about 0.5 μm thick have grain sizes of 1000-2500 Å with a preferred (111) orientation. Above 200°C, the accommodation coefficient of condensation decreases sharply. Regardless of deposition temperature, all films have resistivities of 10^7 ohm-cm or higher, even if dopants are added to the source material. The incorporation of impurities into cadmium telluride and the contribution of incorporated impurities to conductivity depend on the preparation conditions. In the single crystal growth process, indium is an effective donor only if the crystal has been annealed in cadmium vapor to establish a metal excess, and crystals containing copper or gold show p-type conductivity only if a tellurium excess has been formed.(5) If the cadmium telluride films deposited at or below 250°C do not show significant deviations from stoichiometry, neither acceptor nor donor impurities are electrically active. By heating films in evacuated quartz tubes together with small quantities of cadmium, gallium-indium, or tellurium at 500°-575°C for an hour, the dark resistivity has been reduced to about 10^3 ohm-cm. Films annealed in the presence of cadmium showed n-type conductivity while those heated in tellurium were p-type.

The sublimation of cadmium telluride in a hydrogen or an inert atmosphere has been used for the deposition of cadmium telluride films on a variety of substrates including cadmium telluride, cadmium sulfide, sapphire, etc.(6,7) The temperatures of the source and substrate are important parameters affecting the rate of deposition and the properties of the films. Alternately, the direct combination of elemental cadmium and tellurium at the substrate surface has been used for the deposition of cadmium telluride laser windows up to 15 cm^2 in area and 2 mm in thickness.(8) The stoichiometry, carrier concentration, and microstructure can be controlled by adjusting the Cd/Te molar ratio and/or the substrate temperature. The use of high substrate temperature, such as 950°C, has been found to yield windows with the best microstructure and high deposition rates.

Chemical transport technique has been used for the deposition of cadmium telluride films in gas flow and closed-tube systems. For example, epitaxial films of cadmium telluride have been deposited on the basal plane of cadmium sulfide substrates at 500°C by using hydrogen chloride as a transport agent in a gas flow system.(9) Similar epitaxial films have also been obtained in a closed tube at lower growth rates.(10)

In the electrolytic technique, cadmium tellurium films have been plated on indium-tin oxide coated glass substrates at about 90°C using an acid solution of cadmium sulfate and a tellurium anode.(11) The use of low temperature is attractive; however, the grain size is relatively small, about 0.2 μm for a film of 0.2 μm thickness.

I. 3 Cadmium Telluride Solar Cells

The use of cadmium telluride for photovoltaic devices has been under investigation for nearly twenty years. Similar to gallium arsenide, the fabrication of efficient homojunction cadmium telluride solar cells is difficult for at least three reasons: (1) the junction must be shallow because of the short optical absorption length and minority carrier diffusion length in cadmium telluride, (2) The surface layer must be of low electrical resistivity to reduce the series resistance of the device, and the high dopant concentration further reduces the carrier diffusion length, and (3) the surface recombination must be minimized. The highest reported efficiency of cadmium telluride junction solar cell is about 4%.(12)

Improved conversion efficiencies have been obtained by using heterojunction structures. For example, thin film $Cu_2Te/CdTe$ solar cells have been prepared in a manner similar to Cu_2S/CdS solar cells, i.e., an n-type cadmium telluride film vapor-deposited on a molybdenum or glass substrate was treated with a cuprous salt solution to form the heterojunction. Solar radiation is incident on the copper telluride side and is nearly all absorbed by the cadmium telluride; conversion efficiencies of about 6% have been obtained.(13) Thin film solar cells containing both CdS/CdTe and $Cu_2Te/CdTe$ structures on a glass substrate have been reported to have an AM1 efficiency of 8%.(14) In this method, transparent indium oxide was deposited on glass followed by the deposition of a 20 μm 0.2 ohm-cm cadmium sulfide film and a 10 μm cadmium telluride paste by the screen printing method, and the structure was dipped into a cuprous salt solution.

Heterojunction structures between cadmium telluride and other II-VI compounds have also been investigated for solar cell purposes. Since cadmium telluride is the only II-VI compound which can be prepared in both n-type and p-type forms and zinc telluride can only be prepared in the p-type form, the choice of the p-type member is limited to cadmium telluride or zinc telluride. The n-CdS/p-CdTe structure (lattice mismatch: 9.7%) has been studied in detail; cadmium sulfide serves as a window and minimizes the surface recombination of light-generated carriers. N-CdS/p-CdTe heterojunctions have been prepared by close-spaced chemical transport of p-CdTe films onto single crystal n-CdS, by vacuum evaporation of n-CdS films onto single crystal p-CdTe, and by solution spraying of n-CdS films onto single crystal p-CdTe.(15,16) The highest conversion efficiency, about 8%, was obtained by indium-tin oxide coated n-CdS/p-CdTe structures. P-ZnTe/n-CdTe structures (lattice mismatch: 5.8%) have also been prepared by close-spaced chemical transport technique; however, their quantum efficiency was only about 2%. Available data on heterojunction structures indicate no serious loss of photovoltaic performance in transferring from a single crystal to thin films. Furthermore, the commonly accepted assumption that lattice mismatch and high quantum efficiency are mutually exclusive is not necessarily valid; a high local field at the interface can effectively prevent recombination through interface states and permit a large quantum efficiency of the cell.

In another investigation,(17) solar cells with a conversion efficiency of 12% have been produced by the vacuum evaporation of cadmium sulfide on the (111) surface of p-type cadmium telluride crystal grown by the Bridgman technique. These results strongly suggest that thin film cadmium telluride solar cells with 10% or greater efficiency can be achieved with a high probability.

I. 4 Technical Approaches

The overall objective of this program is to demonstrate the feasibility of producing thin film cadmium telluride solar cells with a conversion efficiency of 10% or higher. The technical approaches selected to fulfill this objective consist of (1) the chemical vapor deposition of cadmium telluride films of controlled conductivity type and carrier concentration on a suitable foreign substrate with low CdTe/substrate interface resistance, (2) the characterization of structural and electrical properties of the deposited films, and (3) the fabrication, evaluation, and optimization of thin film cadmium telluride solar cells.

During the first quarter of this program, an apparatus for the chemical vapor deposition of cadmium telluride has been designed and constructed. Many experiments on the deposition of cadmium telluride films on several types of substrates have been carried out, and their structural and electrical properties evaluated. The experimental procedures and results are discussed in the following sections.

II. Chemical Vapor Deposition of Cadmium Telluride Films

II. 1. Selection and Preparation of Substrates

The substrates for the deposition of cadmium telluride films for solar cell purposes must be of low cost and must possess certain electrical, chemical, and mechanical properties. The substrate must provide a low resistance electrical contact to the active layer, must not introduce impurities into the active layer over the long term, and must be mechanically compatible with the active layer over a wide range of temperature and humidity. Furthermore, substrates with high electrical conductivity are preferred so that they may serve as an ohmic contact to the solar cell. The structural properties of the substrate should also be considered since the microstructure and crystallographic properties of cadmium telluride films depend, to a great extent, on the structural properties of the substrate.

Because of the chemical environment in the deposition of cadmium telluride films, the choice of substrates is rather limited. Graphite appears to be an economical substrate for large area solar cells. Several types of graphite, such as grade PLC graphite manufactured by POCO Graphite Incorporated, have a thermal expansion coefficient similar to that of cadmium telluride, $5.5 \times 10^{-6} {}^{o}C^{-1}$. Graphite is chemically inert under the conditions used for the deposition of cadmium telluride. Also, graphite has high thermal and electrical conductivities and may be used as an ohmic contact to the solar cell. Since graphite is porous and the surface of graphite is inhomogeneous, a thin layer of carbon, silicon, or tungsten was used to provide a more impervious and uniform surface.

The coating of the graphite surface with carbon, silicon, or tungsten is a well-established technology. They were deposited by the thermal decomposition of propane at 1100°-1200°C in an argon atmosphere, thermal reduction of trichlorosilane with hydrogen at 1100°C, and the thermal reduction of tungsten hexafluoride with hydrogen at 450°-550°C, respectively. The thickness of the coatings is usually 2-3 μm.

In addition to coated graphite, Coors 183J mullite with a thermal expansion coefficient of $4.3 \times 10^{-6}\,{}^{o}C^{-1}$ was also used as a substrate. The use of an insulating substrate could facilitate the characterization of the electrical properties of cadmium telluride films.

II. 2. Deposition of Cadmium Telluride Films

The chemical vapor deposition technique in a gas flow system has been used extensively for the deposition of semiconductor films. This technique has two distinct advantages: (1) a wide range in thickness from a fraction of a micrometer to hundreds of micrometers can be achieved and controlled, and (2) the dopant concentration and distribution in the deposit can be controlled to an extent not obtainable by other techniques. It is essential that the chemical reaction is predominately heterogeneous taking place on the substrate surface. In contrast, volume reaction results in the formation of molecular clusters of random orientations in the space surrounding the substrate, and the deposition of these clusters on the substrate will produce non-adherent deposit. Furthermore, the by-products of the reaction must be volatile at the processing temperature to insure high purity of the deposit.

Two types of reactions have been selected for the deposition of cadmium telluride films:

(1) Reactions between elemental cadmium and tellurium

$$2\ Cd(g) + Te_2(g) \rightarrow 2\ CdTe\ (s)$$

(2) Reactions between cadmium iodide and tellurium in a hydrogen atmosphere

$$2\ H_2(g) + 2\ Cd\ I_2(g) + Te_2(g) \rightarrow 2\ Cd\ Te(s) + 4\ HI\ (g)$$

The apparatus used for the deposition of cadmium telluride films is shown schematically in Fig. 4. It consists of two parts: a gas flow control panel and a reaction tube containing cadmium, tellurium, and substrate at appropriate temperatures. On the gas control panel, flowmeters and valves are used to control the flow of hydrogen, hydrogen iodide, and phosphine (a p-type dopant). Hydrogen is used to carry cadmium and tellurium vapors into the reaction tube. Cadmium iodide is prepared in-situ by passing hydrogen iodide through the cadmium container. The fused silica reaction tube is of 55 mm ID and 59 mm OD; the use of a relatively large diameter reaction tube facilitates the preparation of large area cadmium telluride films of uniform properties. The reaction tube is held in a three-zone resistance-heated furnace with each zone separately heated and controlled.

To carry out the deposition of cadmium telluride, a cadmium container, a tellurium container, and the substrate are placed in the appropriate temperature zones. Hydrogen is introduced into the cadmium and tellurium containers to carry the reactants to the substrate surface where the chemical combination takes place depositing cadmium telluride. The initial partial pressures of cadmium and tellurium at the substrate surface, P^o_{Cd} and $P^o_{Te_2}$, may be estimated from the temperatures of cadmium and tellurium and the flow rates of hydrogen through the sources and the reaction tube. When $P^o_{Cd}(P^o_{Te_2})^{\frac{1}{2}}$ is higher than the dissociation constant of cadmium telluride at the substrate temperature, K_{CdTe}, the deposition of cadmium telluride takes place so that the partial pressures

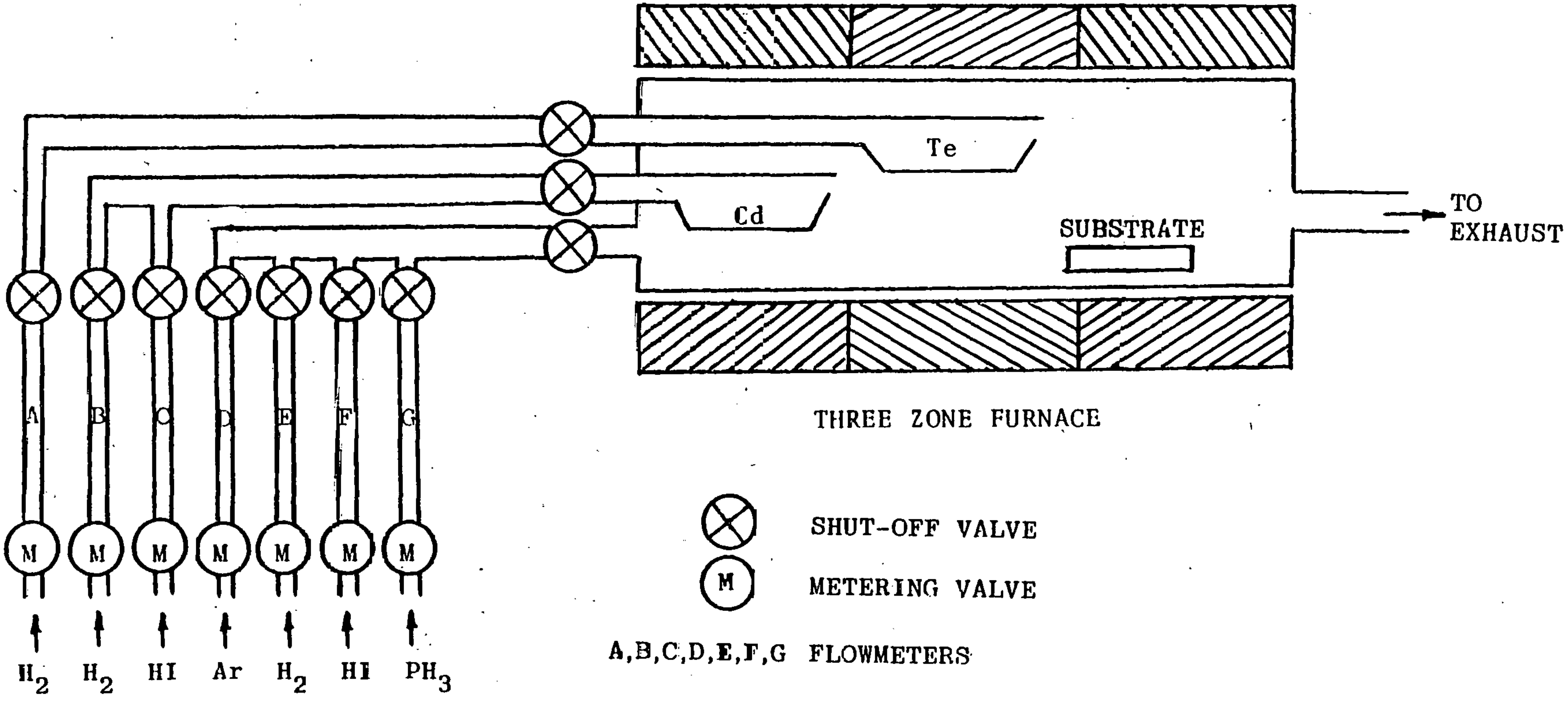


Fig. 4 Schematic diagram of the apparatus for the deposition of cadmium telluride films.

of cadmium and tellurium are reduced to P_{Cd} and P_{Te_2}, respectively, in order to satisfy the relation

$$P_{Cd}(P_{Te_2})^{\frac{1}{2}} = K_{CdTe}$$

The deposition rate of cadmium telluride is determined by the degree of supersaturation of cadmium and tellurium at the substrate surface and is given by:

$$n_{CdTe} = (P^o_{Cd} - P_{Cd}) \; V / RT$$

$$= 2 \; (P^o_{Te_2} - P_{Te_2}) \; V / RT$$

where V is the total gas flow rate. Thus, the reactant composition and substrate temperature are important parameters determining the deposition rate of cadmium telluride.

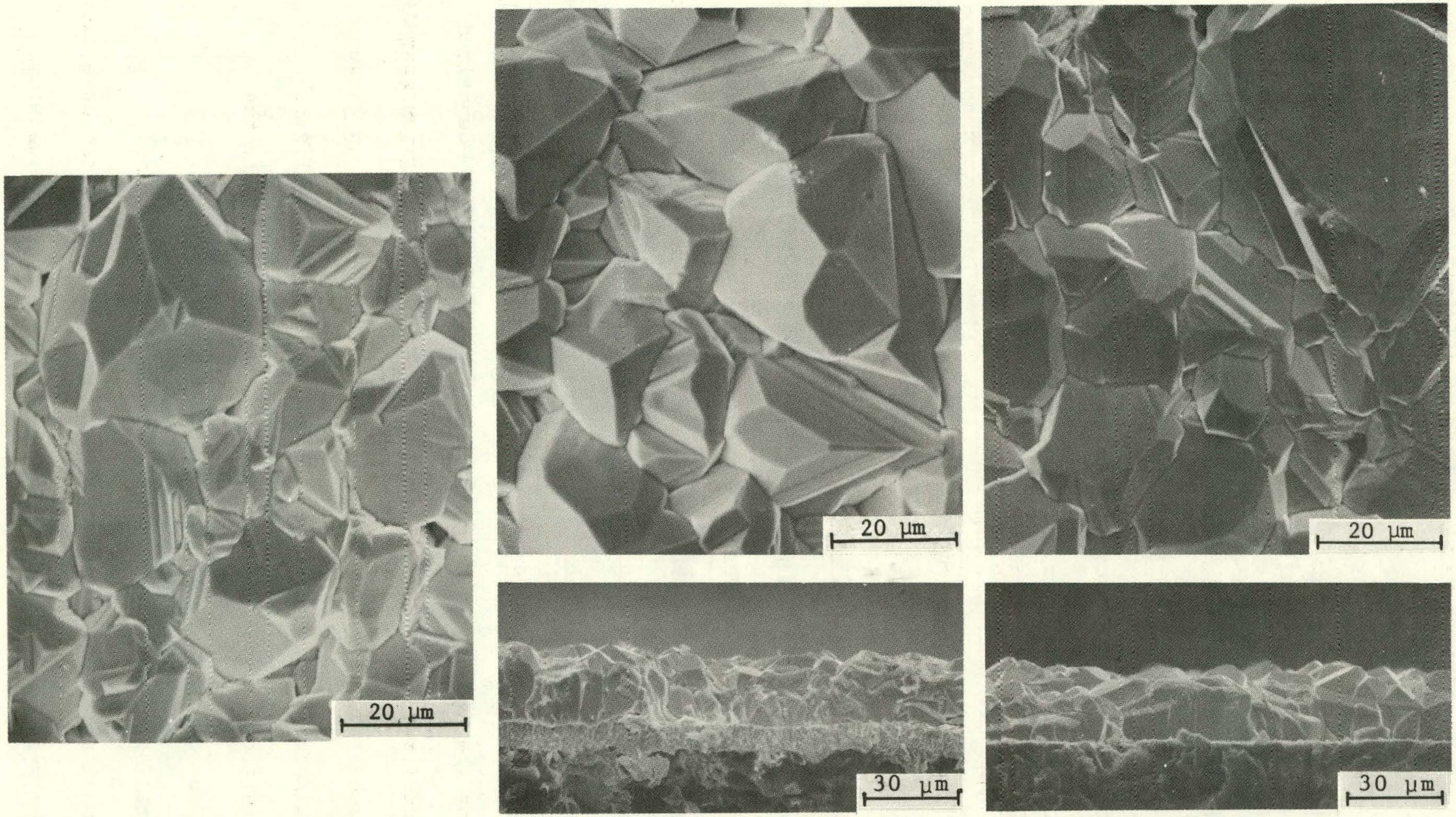
Many deposition experiments have been carried out under a wide range of conditions using mullit , carbon/graphite, silicon/graphite, and tungsten/graphite as substrates, and the substrate was usually of 3 cm X 3 cm area. The effects of the temperature of substrate was first investigated; the partial pressures of cadmium and tellurium were in the range of (2.5-13) $\times 10^{-4}$ and (5-25) $\times 10^{-4}$ atm, respectively, and the total flow rate of hydrogen was 2 ℓ/min. At substrate temperatures of 550°C or below, the deposit was always non-adherent due to the contribution of homogeneous nucleation associated with the high degree of supersaturation in the substrate zone. This problem could be overcome by using lower partial pressures of cadmium and tellurium in the reactant mixture. However, the deposition rate will be too low for practical applications. For example, the equilibrium partial pressures of tellurium over cadmium telluride are approximately 3×10^{-9} and 2.6×10^{-7} atm at 400° and 500°C, respectively. Assuming that a supersaturation of 1000 in the partial pressures of cadmium and tellurium can be tolerated without appreciable homogeneous nucleation, the deposition rates of cadmium telluride are approximately 1.6×10^{-5} and 1.1×10^{-7} moles/min, respectively (or 5×10^{-3} and 0.15 μm/min, respectively, if all cadmium telluride deposited on a substrate of 10 cm^2 area). Therefore, high deposition rates can only be achieved at high substrate temperatures, where high partial pressures of cadmium and tellurium can be used without any appreciable contribution of homogeneous reactions. Also, the use of high substrate temperature promotes the deposition of large grain films. However, the rate of nucleation is reduced at high substrate temperatures, and this could result in the formation of discontinuous films.

III. Properties of Cadmium Telluride Films

III. 1 Structural Properties

Cadmium telluride films have been deposited on mullite, graphite, carbon/graphite, silicon/graphite, and tungsten/graphite substrates in the temperature range 550° - 740° C. With the exception of the deposit on silicon/graphite, all films are tightly adherent to the substrate. The deposited cadmium telluride films are polycrystalline, and the as-deposited and vertical cross-sectioned surfaces were examined with optical and scanning electron microscopes to determine the microstructure and the average deposition rate. The temperature of the substrate is the most important factor determining the average grain size in the films. Figure 5 shows the as-deposited surfaces of cadmium telluride films deposited on mullite, tungsten/graphite, and graphite substrates at 580°C, and the vertical cross-sectioned surfaces of CdTe/W/graphite and CdTe/graphite specimens. These films are approximately 20 μm in thickness, deposited at a rate of about 0.7 μm/min. Many grains in the films are up to 20 μm in size and have well-developed faces. The micrographs of the cross-sectioned surfaces indicate that not all grains are columnar, i.e., random nucleation occurred during the deposition process. Figure 6 shows the as-deposited surfaces of cadmium telluride films deposited on mullite, tungsten/graphite, and graphite substrates at 740°C. It is apparent that grains in these films are considerably larger than those deposited at 580°C (Fig. 5). However, the surface becomes relatively rough due presumably to the dependence of the growth rate on crystallographic orientation.

The crystallographic properties of cadmium telluride films deposited on mullite, tungsten/graphite, and graphite substrates have been examined by the x-ray diffraction technique. Polycrystalline cadmium

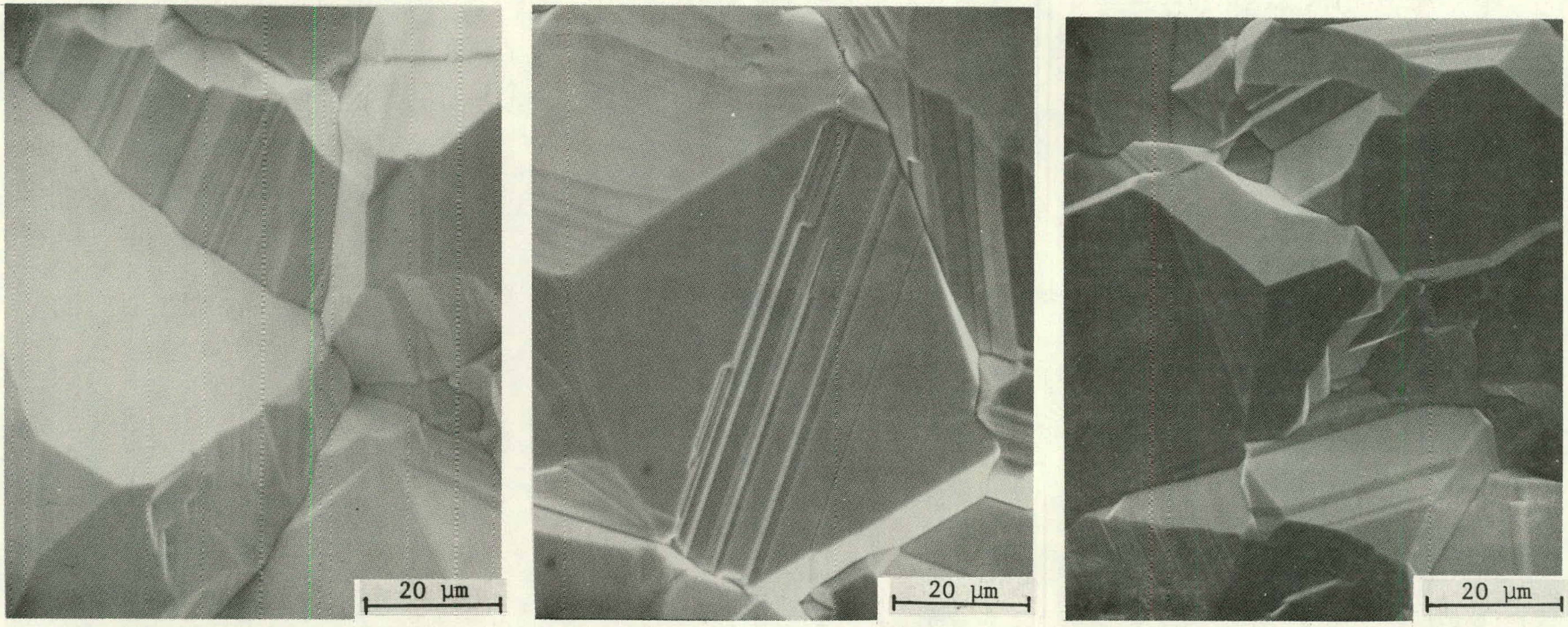


Mullite Substrate

Tungsten/Graphite Substrate

Graphite Substrate

Fig. 5 As-deposited and vertical cross-sectioned surfaces of cadmium telluride films deposited on mullite, tungsten/graphite, and graphite substrates at 580°C.



Mullite Substrate **Tungsten/Graphite Substrate** **Graphite Substrate**

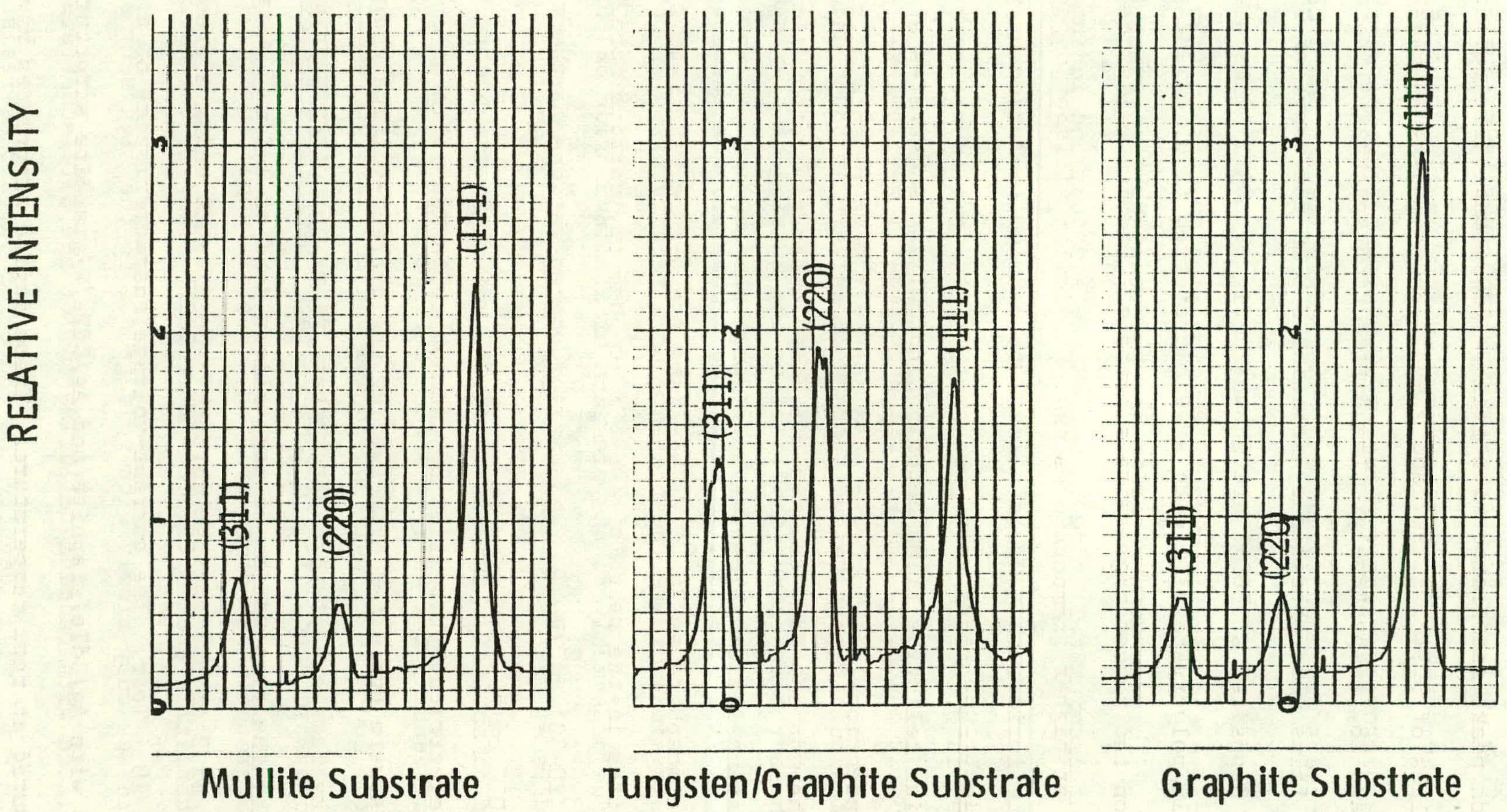
Fig. 6 As-deposited surfaces of cadmium telluride films deposited on mullite, tungsten/graphite, and graphite substrates at 740°C.

telluride powder of random orientations is known to show three strong diffraction peaks associated with {111}, {220}, and {311} reflections with d values of 3.742, 2.290, and 1.954 Å and relative intensities of 100, 62, and 28, respectively. The diffraction spectra of the cadmium telluride films were obtained by scanning 2 Θ in the range of 20-60°, and those deposited at 580°C are shown in Fig. 7. All films are essentially polycrystalline with a weak preferred {110} orientation in the film on the tungsten/graphite substrate. Cadmium telluride films deposited at higher temperatures exhibit similar diffraction spectra.

III. 2 Electrical Properties

Cadmium telluride films deposited on mullite substrates at 580°C without intentional doping were used for Hall measurements at room temperature by the van der Pauw technique. Ohmic contacts to the films were made by evaporating indium through a metal mask followed by annealing in a hydrogen atmosphere at 200°C. The films are n-type with room temperature resistivities in the range of (4-7) X 10^4 ohm-cm, carrier mobilities in the range of (20-30) cm^2/V-sec, and carrier concentrations in the range of (6-9) X 10^{12} cm^{-3}.

The electrical properties of cadmium telluride films on conducting substrates were evaluated by measuring the current-voltage characteristics of Schottky barriers prepared from these films. Schottky barriers were prepared by the evaporation of many silver dots of 1-2 mm^2 area onto the specimens of 3 cm x 3 cm area through a metal mask under a pressure of less than 10^{-6} Torr. The current-voltage characteristics of a number of specimens with Ag/CdTe/graphite and Ag/CdTe/W/graphite structures have been measured at room temperature. These device structures have been found to have a very high dark resistance in both forward and reverse directions. An example of the current-voltage characteristics of a



Mullite Substrate

Tungsten/Graphite Substrate

Graphite Substrate

Fig. 7 X-ray diffraction spectra of cadmium telluride films deposited on mullite, tungsten/graphite, and graphite substrates at 580°C.

Ag/CdTe/W/graphite diode is shown in Fig. 8. The low dark currents indicate that in addition to Ag/CdTe, the CdTe/W interface is also rectifying. The current is increased appreciably by illuminating the diode with a microscope light. Also, a significant fraction of the Schottky barriers has been found to be shorted indicating the presence of pinholes in the films.

To overcome the interface rectification problem, a thin film of aluminum or indium was evaporated to the substrate surface prior to the deposition of cadmium telluride films. Since aluminum and indium are donors in cadmium telluride, they would alloy with cadmium telluride to yield a heavily doped interface region, thus facilitating the formation of low-resistance ohmic contacts. In several experiments, cadmium telluride films were deposited on Al/graphite substrate successively at 580°C and 700°C; the use of higher temperature should allow the melting of aluminum and subsequent alloying with cadmium telluride. However, the current-voltage measurements again indicate the presence of a rectifying CdTe/substrate interface, due presumably to the presence of aluminum oxide on the substrate surface.

The use of an indium interlayer of 1-2 μm thickness appears to be effective in reducing the CdTe/substrate interface resistance, due presumably to the low melting point of indium and the ease of reduction of indium oxide by hydrogen. The current-voltage characteristics of a Ag/CdTe/In/W/graphite structure of 1 mm^2 area are shown in Fig. 9. The dark characteristics are no longer symmetrical; however, the forward current increases only slowly with voltage due to the high series resistance associated with cadmium telluride and/or the CdTe/substrate interface. Further work will identify the source of the series resistance. The

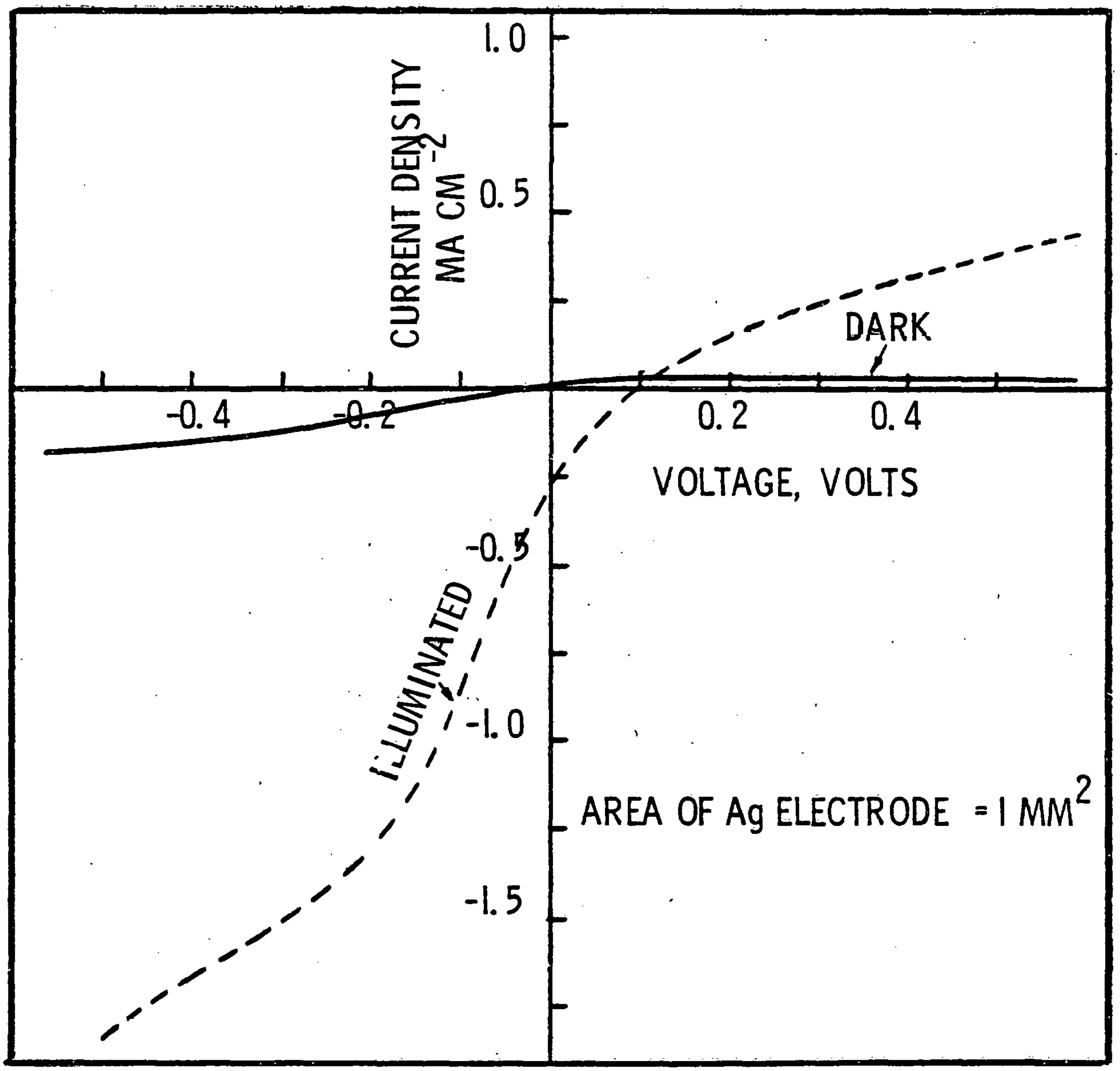


Fig. 8 Current-voltage characteristics of a Ag/CdTe/W/graphite structure suggesting the presence of a rectifying CdTe/substrate interface.

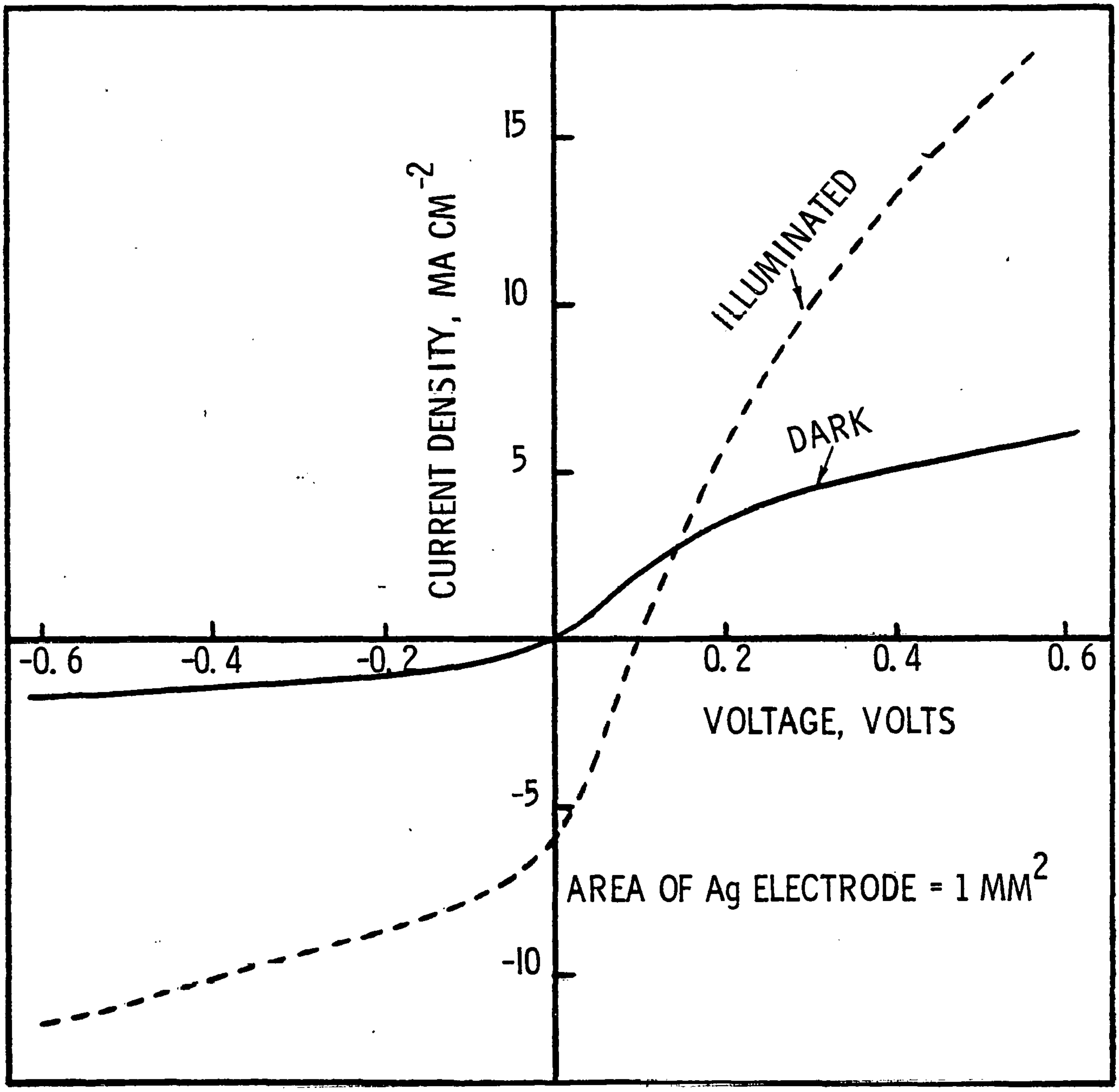


Fig. 9 Current-voltage characteristics of a Ag/CdTe/In/W/graphite structure.

use of an indium interlayer has also reduced significantly the concentration of pinholes in cadmium telluride films.

Preliminary work on the fabrication of thin film cadmium telluride solar cells has also been carried out. Several Schottky barrier solar cells of 0.25 cm^2 area have been prepared from cadmium telluride films on In/W/graphite substrates. A silver film of 60-80 Å thickness was evaporated onto the surface of cadmium telluride films, and the grid contact was formed by evaporation through a mask. Figure 10 shows the current-voltage characteristics of a solar cell under illumination with ELH quartz halogen lamps at AM1 conditions. The open-circuit voltage, short-circuit current density,and fill factor are approximately 0.25 V, 11 mA/cm^2, and 36%, respectively, corresponding to an AM1 efficiency of about 0.8%. The relative low open-circuit voltage is due mainly to the low barrier height of the Ag/CdTe structure, and the low fill factor is due to the high series resistance in the structure.

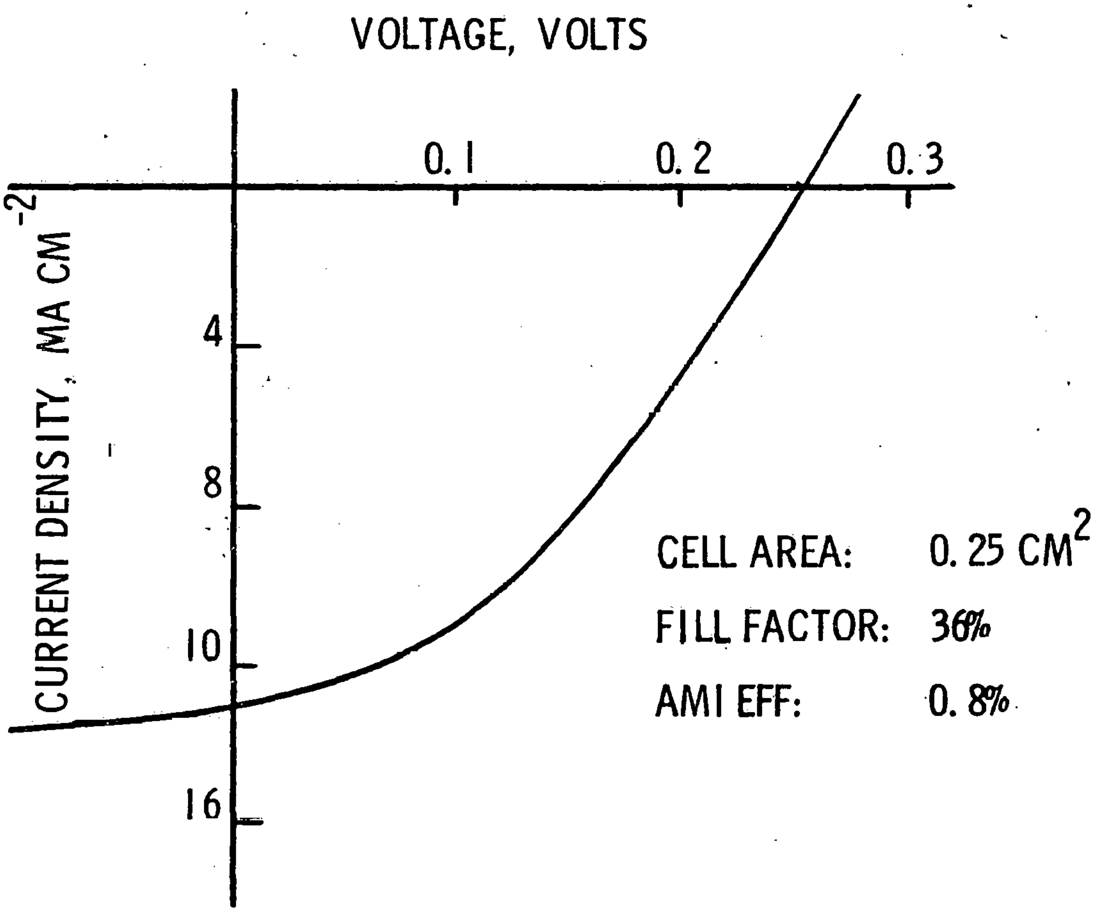


Fig. 10 Current-voltage characteristics of a Schottky barrier thin film cadmium telluride solar cell under AM1 conditions.

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V. Plan for the Next Period

Cadmium telluride films for solar cell purposes must have (1) pinhole-free structure and good adherence to the substrate, (2) low CdTe/substrate interface resistance, and (3) controlled conductivity type and electrical resistivity. During the next period, efforts will be directed to the elimination of pinholes in cadmium telluride films, the measurement of CdTe/In/W/graphite interface resistance, and the control of resistivity of cadmium telluride films by using n-type (indium and iodine) and p-type (phosphorus) dopants.