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THIN FILMS OF InP FOR PHOTOVOLTAIC ENERGY CONVERSION

First Quarterly Technical Progress Report for July 5–September 28, 1979

By
Harold M. Manasevit
Ralph P. Ruth
Lavada A. Moudy
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Richard E. Johnson

November 1979

Work Performed Under Contract No. AC02-79ET23004

Rockwell International
Electronics Research Center
Anaheim, California

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Dr. Kim Mitchell, of the Photovoltaic Program Office of the Solar Energy Research Institute, Golden, CO, is the DoE-designated Technical Manager for this contract.

ABSTRACT

A research study is in progress to develop a low-cost high-efficiency thin-film InP heterojunction solar cell, using the metalorganic chemical vapor deposition (MO-CVD) technique for InP film growth on suitable low-cost substrates. Heterostructure devices of CdS/InP and indium tin oxide (ITO)/InP are to be prepared by Stanford University under subcontract, using the InP films grown by MO-CVD. The first quarter's work is summarized.

An existing reactor system was modified and upgraded, with provision for growth of GaAs intermediate layers and p-type doping capability using a premixed metalorganic Zn compound source, as well as a dilution system common to the dopants and the Group III and Group V reactants. The all-fused-quartz deposition chamber was redesigned to permit use of larger susceptors and to facilitate assembly, disassembly, and cleaning. Film growth rate profiles were obtained, and the background doping characteristics of the system were determined and found to be n type, with a thermal activation energy of $\sim 1.8\text{eV}$ associated with the process.

Initial attempts to prepare p-type epitaxial InP films on single-crystal InP substrates met with only limited success until a new source of diethylzinc (DEZn) was obtained and installed on the system, after which active Zn concentrations (i.e., measured hole concentrations) in the 10^{17}cm^{-3} range were produced in epitaxial films on (100), (111A), and (111B) InP substrates in the deposition temperature range 715–730°C. As in earlier studies, the observed Zn uptake in these films varied with crystallographic

orientation, with a given Zn concentration in the deposition chamber being incorporated most readily in (111A) films and least readily in (111B) films, with (100) films intermediate between the two.

The films have been characterized by x-ray and electron diffraction analyses, examination in the scanning electron microscope, and determination of transport properties by Hall-effect measurements using the van der Pauw method. Results of these investigations are reviewed.

Work planned for the next quarter is outlined.

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1. INTRODUCTION

The Electronics Research Center of Rockwell International is undertaking a one-year research study to develop a low-cost high-efficiency thin-film InP heterojunction solar cell, using the metalorganic chemical vapor deposition (MO-CVD) technique for InP film growth on suitable substrates. Heterostructure devices of CdS/InP and indium-tin oxide (ITO)/InP are to be prepared and characterized by the Department of Materials Science and Engineering of Stanford University, under subcontract.

The contract work is directed toward achievement of the Department of Energy goals for thin-film polycrystalline solar cells on low-cost substrate materials - namely, AM1 photovoltaic conversion efficiencies of 10 percent or greater by 1980 and cost feasibility of \$0.30 per peak watt (electric) by 1986.

The research effort involves three major technical tasks:

- I. Materials Growth
- II. Materials Characterization
- III. Device Fabrication and Characterization.

The principal subtasks for each of these are defined in the contract Statement of Work as follows:

Task I - Materials Growth

1. Investigate further the growth of thin films of InP on low-cost substrates by the standard MO-CVD process
2. Select substrates which will promote the growth of InP with the required photovoltaic properties

3. Investigate growth in a He carrier gas and growth at reduced pressures in terms of the properties of polycrystalline InP
4. Investigate nucleation and early-stage growth of InP films on low-cost substrates
5. Investigate the use of Cd as a suitable p-type dopant for MO-CVD InP and the use of in situ diffusion/annealing processes for improved doping.

Task II - Materials Characterization

1. Measure structural, electrical and optical properties of films grown by the process of Task I and provide definitive information regarding the photovoltaic potential of the various alternate processes
2. Investigate by x-ray, TEM and SEM techniques the preferred orientation, grain size, grain perfection and other structural properties of the films grown by the various processes described above. Determine transport properties of the polycrystalline films and their relation to preparation techniques
3. Determine by SEM and optical techniques the photovoltaic properties and potential of the InP films.

Task III - Device Fabrication and Characterization

1. Make state-of-the-effort CdS/InP and/or IT0/InP solar cell devices and characterize them by taking I-V curves under solar or simulated solar irradiation.

In addition to carrying out the three main technical tasks, Rockwell will deliver representative experimental solar cells and associated photovoltaic performance data to DoE quarterly beginning with the third quarter, as specified in the contract Statement of Work.

This constitutes the first Quarterly Technical Progress Report for this program and covers the period from the contract effective date - July 5, 1979 - through September 28, 1979. Technical progress during this period is described by task in the next section. Section 3 gives a summary of the work, with appropriate conclusions, and Section 4 an outline of work planned for the second quarter.

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2. TECHNICAL PROGRESS

The activities of the three main technical tasks during the first quarter of the program are described in this section. A summary is given in Section 3.

2.1 TASK I - MATERIALS GROWTH

The initial work of this task involved modification of an existing metalorganic chemical vapor deposition (MO-CVD) reactor system for use in this program. Upon completion of the necessary work on the reactor system, experimental deposition of undoped epitaxial InP films was undertaken, followed later in the quarter by the preparation of Zn-doped p-type epitaxial InP films. These three activities are described below.

2.1.1 MO-CVD Reactor System Modification and Test

The MO-CVD reactor system built for and used in an earlier DoE-sponsored contract (Ref. 1) is being used for this contract, as well. The system remained largely intact and unmodified in the period between the two contract programs, although it was used for some other Rockwell MO-CVD investigations involving related materials systems. Thus, it was necessary to test and/or disassemble and thoroughly clean all sections of the reactor system, as an absolute minimum procedure, and some modifications were also made.

The initial testing procedure indicated that several system leaks had developed since the last use of the system, most of those occurring in those joints in which Teflon ferrules had been employed in the Swagelok fittings. Such ferrules were replaced with plated stainless steel ferrules, and all other joints in portions of the system expected to be permanently closed (that is, not subject to frequent disassembly for cleaning or modification) were similarly upgraded with the stainless steel ferrules. All parts necessary for

making the reactor system operational were obtained, and the modified (see below) and upgraded system was ready for test and initial experimental deposition runs in the second month of the program.

Because the lead time on delivery of some of the metalorganic reactants required for this program was at least 30 days and since it was not possible to place orders for those reactants until the contract start date had been committed to Rockwell by DoE, it was necessary to borrow reactants from other Rockwell programs in order to begin experimental work when the reactor system first became available. The borrowed materials were to be subsequently replaced from contract supplies when they were later received.

Modifications were made in the system relative to the configuration in use at the conclusion of the previous DoE-sponsored InP contract. Three principal changes were introduced. First, provisions for deposition of GaAs films by the MO-CVD process was added so that such layers can be formed as an integral part of the growth sequence for preparing InP cell structures. This capability was added because the earlier InP solar cell contract work (Ref. 2) had shown that polycrystalline p-type (Zn-doped) films of InP could be successfully formed on polycrystalline GaAs films grown by MO-CVD (in a separate reactor system at that time) on low-cost substrate materials (e.g., Mo), while deposition of similarly doped InP polycrystalline films directly on the low-cost substrate material resulted only in films of very high resistivity.*

The other two principal system modifications that were made were incorporation of a p-type doping capability using a premixed source tank of H₂ doped with dimethylzinc (DMZn), and addition of a provision for diluting this

*An area of investigation in the present program is to find an explanation for this effect and, more generally, to identify the structural location of the added Zn impurity in the polycrystalline InP films and the fraction of added dopant that is electrically active.

premixed DMZn source with additional H_2 gas. The H_2 diluent can also be fed into the diethylzinc (DEZn) source or a dimethylcadmium (DMCd) source, as required.

A detailed schematic diagram of the modified InP reactor system as prepared in the first month of the contract is given in Figure 1. The quartz deposition chamber used with this system at the start of this program was replaced by a chamber with a larger base joint, to accommodate new and somewhat larger-diameter susceptors and facilitate handling and cleaning procedures, in the second month of the program. The modified deposition chamber is shown in Figure 2.

The first experiments with the reactor system were for the purpose of testing the integrity of the system and establishing its overall performance, and were begun in the second month. Previously established (Ref. 2) deposition parameters were used as a guide in selecting the conditions to be used in operating the system, and the system as modified passed the preliminary tests with no serious malfunctions or other problems.

There was evidence, on the basis of the first few deposition experiments, that the new triethylindium (TEIn) source being used was chemically "clean" and probably equivalent to sources previously found adequate for growth of good quality epitaxial InP films. This was indicated by the fact that the powdery deposit generated at the point of mixing of the TEIn and the PH_3 was white rather than yellow (the latter an indication of contaminated TEIn), and was verified by the overall quality of the epitaxial films grown later in the reporting period (see below).

Typical InP deposition (i.e., film growth) rate profiles for the MO-CVD reactor system and deposition chamber, as obtained on two different occasions (about 10 days apart), are shown in Figure 3. The useful region of relatively uniform growth rate is seen to be approximately 1 cm in diameter, centrally located on the susceptor of ~ 5 cm diameter. The new deposition chambers and larger-diameter susceptors put into use in the second month had

Figure 1. Schematic Diagram of Modified InP MO-CVD Reactor System.

Figure 2. Modified All-quartz Deposition Chamber
Used on MO-CVD Reactor System of Figure 1 for Growth
of InP Films by TEI-PH₃ Reaction In H₂ Atmosphere.

no observable effect on the film growth rates obtained in this central region.

Figure 3. Typical Growth-rate Profiles for InP Deposition on Susceptor in Chamber Shown in Figure 2.

2.1.2 Growth of Undoped Epitaxial InP Films

The initial InP deposition experiments, including the above preliminary experiments for the purpose of testing the reactor system, were carried out with substrates of single-crystal InP. A variety of InP substrate wafers was ordered from Metals Research, Inc., for use in this program, but long delivery times were indicated by the supplier. In fact, none of the ordered material was received during the period covered by this report.

Consequently, as in the case of the metalorganic reactants, substrate material was borrowed from other Rockwell programs, to be replaced later. This avoided excessive delay in the start of the experimental program.

Experiments were carried out to establish the background doping concentration in the system and the overall quality of the InP films prepared in the modified system with the reactants then being used. The first experiments indicated that undoped InP epitaxial films grown on (100) and (111A) orientations of InP substrates at $\sim 725^{\circ}\text{C}$ exhibited electron concentrations (measured by the van der Pauw technique at room temperature) of $\sim 1 \times 10^{17} \text{ cm}^{-3}$, somewhat higher than the levels seen in the earlier work (Ref. 2) for these orientations and this growth temperature.

Undoped films were then deposited on (100)-oriented InP:Fe single-crystal substrates at temperatures ranging from 625 to $\sim 685^{\circ}\text{C}$ to supplement the experiment done at $\sim 725^{\circ}\text{C}$. The deposition rates in all cases were approximately $0.2 \mu\text{m}/\text{min}$.

Results of van der Pauw measurements of transport properties (Task II) of these films indicated there was background donor doping in the system that was $8 \times 10^{15} - 1 \times 10^{16} \text{ cm}^{-3}$ (measured electron concentration) for deposition at 625°C ; $\sim 1 \times 10^{16} \text{ cm}^{-3}$ at $\sim 650^{\circ}\text{C}$; $2-3 \times 10^{16} \text{ cm}^{-3}$ at $680-685^{\circ}\text{C}$; and $\sim 7 \times 10^{16} \text{ cm}^{-3}$ at 720°C .

Although there was considerable scatter in the data obtained for this particular growth orientation, it appeared that the background donor doping was temperature-activated, with an activation energy of approximately

1.8 eV. An activation energy of such magnitude is often found for thermally activated surface-controlled processes in heterogeneous gas reactions and suggests the possibility of the background doping being surface-controlled rather than gas-transport-controlled in this system. The background doping for other growth orientations was to be established in later experiments.

2.1.3 Growth of Zn-doped p-type Epitaxial InP Films

Initial InP deposition experiments with Zn doping were carried out late in the second month, using as the dopant source a tank of diethylzinc (DEZn) that was already on hand at the start of the contract program, having been obtained and used for another Rockwell program. The experimental conditions used in these experiments were those established in previous studies (Ref. 2).

It was found that very low concentrations of DEZn (e.g., 0.5 to 5.0 ccpm of H₂ carrier gas through the DEZn source bubbler, maintained at 0°C) in the reactor chamber were not sufficient to convert the epitaxial InP films to p type on either (100)-oriented or (111A)-oriented InP substrates, whereas similar DEZn additions had been adequate for growth of p-type films in the earlier studies. It seemed probable that the higher background donor doping experienced in the present system was responsible for this result.

Increasing the DEZn flow rate somewhat did produce p-type films. Hole concentrations in the 10^{17} - 10^{18} cm⁻³ range were finally produced for growth at ~ 725°C by H₂ flow rates of 10 ccpm or more over the DEZn.

Although such carrier concentrations were achieved in films grown with the larger DEZn additions (up to 25 ccpm of H_2 over the DEZn source), the films generally had relatively rough surfaces and looked as if either a chemical contaminant or a physical perturbation had interfered with the deposition process. The SiC-covered graphite susceptors used for the first experiments subsequently developed cracks in the top surfaces and exhibited some separation at the SiC-graphite interfaces, suggesting a possible source of contamination in the above experiments. New susceptors of slightly larger (2.2 in) diameter were borrowed from another Rockwell program (susceptors ordered specifically for this contract work had not yet been delivered) and were used for this work, and the subsequent results were more satisfactory.

Additional deposition experiments were then conducted in the 650-725°C range to attempt to obtain reproducibly InP epitaxial films (on InP substrates) that were p type, with active doping (i.e., carrier) concentrations in the 10^{16} - 10^{17} cm^{-3} range. To achieve this controlled lower concentration of p-type doping it was again found necessary to "proportion" the gas flow passing through the DEZn dopant source (maintained at 0°C), as in previous studies of this MO-CVD system, to achieve sufficiently dilute concentrations of DEZn in the reactant gas mixture in the deposition chamber. By this expedient it was possible to achieve measured hole concentrations (and thus - presumably - active acceptor doping concentrations) of $4-9 \times 10^{18}$ cm^{-3} in (100)-oriented films, $2-3 \times 10^{18}$ cm^{-3} in (111B)-oriented films, and $6-8 \times 10^{17}$ cm^{-3} in (111A)-oriented films, with little if any detectable dependence upon the growth temperature in the 650-725°C range. The surface

quality of many of these films continued to be poor, however, as was found for the first Zn-doped films grown earlier.

Late in the third month the new DEZn source tank that had been ordered at the start of the contract was received from the vendor and immediately installed on the reactor system. Almost immediately an improvement in the surface structure of Zn-doped films on single-crystal InP:Fe substrates was observed, and the significance of continued controlled doping experiments is now expected to improve accordingly.

The doping experiments done with the new DEZn source, employing InP substrates of (100), (111A), and (111B) orientations and deposition temperatures in the 715-730°C range, resulted in measured hole concentrations as low as $4 \times 10^{17} \text{ cm}^{-3}$ in (100)-oriented films - nearly an order of magnitude less than the typical concentration seen in the Zn-doped films of the same orientation prepared with the old DEZn source earlier in the quarter.

However, the same wide variation in Zn uptake for InP growth on (100), (111A), and (111B) orientations that had been found in the earlier studies (Ref. 2) was observed in these experiments. Thus, in those runs in which a (111A)-oriented InP:Fe substrate was present the film grown on it always exhibited the highest carrier concentration, while films grown on the (111B)-oriented substrates often remained n type whereas companion films of either or both of the other two orientations were converted to p type. The cause of this behavior remains unidentified but the problem will continue to be explored.

In the description of the MO-CVD reactor system in Section 2.1.1 it was indicated that among the changes made in the existing system to be used in this program were provision for use of a p-type dopant source consisting of a premixed source tank of H_2 doped with dimethylzinc (DMZn) as well as provision for diluting such a source with additional H_2 gas. A tank of DMZn in a H_2 carrier at ~ 150 ppm dilution that had been ordered for a previous program and which had never been used was returned to the vendor early in this program, after storage for about a year, for recalibration and subsequent use.

The dopant was found by the vendor to be completely depleted, indicating a potential problem in using such a dopant source over an extended period of time without frequent recalibration, either by analytical techniques or by "use techniques." The loss of dopant could be attributed to any one of a number of possible causes, such as the following: (1) DMZn may be naturally unstable; (2) DMZn decomposition could have been catalyzed by impurities on the walls of the tank or by the material of the walls themselves; (3) traces of moisture and/or air in the tank could have reacted with the DMZn. In any case, because of the uncertainty that would exist when using a diluted dopant source which may be unstable, it was decided to postpone studies using DMZn-in- H_2 and continue with the present technique involving DEZn as the source of Zn dopant.

2.2 TASK II - MATERIALS CHARACTERIZATION

The activities of this task began in the second month, as soon as the first InP films were grown in the modified and tested system. The work has

included film structural analyses by x-ray and electron diffraction methods, film morphology examinations and film thickness determinations in the scanning electron microscope (SEM), and measurement of film transport properties by means of the Hall effect, using the van der Pauw method. It was also intended that doping concentrations (i.e., carrier densities) be determined in selected p-type films by the formation and characterization of Schottky barriers, but suitable samples did not become available for such measurements during the period covered by this report.

The required measurements of film thicknesses were made initially in the SEM on cleaved cross-sections of the film-substrate composites. However, identification of the interface has often been difficult, especially for the case of undoped InP films on single-crystal InP substrates. An A-B etch (Ref. 3) was used to help delineate the interface, especially on the (100)-oriented undoped samples. In earlier studies in which this etch was used it did not appear that the etch rate was orientation-dependent for InP.

However, it was found on some of the samples examined in this program that the film-substrate interface contained arrays of holes or voids that were delineated and enlarged by prolonged etching. These holes may be characteristic of an unstable thermally etched P-deficient InP region, and may be related to the gray appearance that characterizes a growing InP film on a (100) surface in the early stages of development of the film. This "gray stage" eventually disappears and the film typically becomes highly reflective as the thickness increases; the duration of the gray stage has appeared to be sensitive to the growth temperature. The observed holes may have been caused

by preferential etching of minute droplets of In produced and trapped at the interface by the thermally induced loss of P, even in the PH_3 -rich atmosphere normally used during film growth.

The etch rate of (100)InP (in the $\langle 100 \rangle$ direction, normal to the (100) plane) was found to be quite low for the A-B etch used.* Essentially no change in thickness of the film was observed as a result of immersion of a sample in the etch for 5 min at room temperature. However, the possible dependence of this etch rate upon doping concentration in the InP has not yet been investigated.

Room-temperature transport properties of various InP films, both undoped and doped p type, were determined by Hall-effect measurements using the van der Pauw method. Contacts to n-type InP consisted of In dots, while In-Ga-Zn preforms were used for contacts to p-type Zn-doped InP. Results of some of those measurements were discussed in Section 2.1.

2.3 TASK III - DEVICE FABRICATION AND CHARACTERIZATION

Most of the effort on this task is to be carried out by personnel of the Department of Materials Science and Engineering at Stanford University under a subcontract. Professor R. H. Bube is the Principal Investigator on the subcontract, although other personnel - including one or more graduate students - are also involved. The subcontract negotiations were concluded

*Etch was 1:1 mixture of 40cc H_2O + 0.3g AgNO_3 + 40cc HF and 40g CrO_3 + 40cc H_2O .

late in the quarter, although preliminary work was begun earlier.

In addition, some device fabrication and characterization is expected to be done at Rockwell, but that activity will be a relatively minor part of the contract work during the first year. One purpose of the device work to be done at Rockwell is to provide a periodic verification of the device performance results obtained at Stanford, to minimize the likelihood of systematic or other processing or measurement errors affecting the results obtained at any one laboratory.

The preliminary work begun at Stanford consisted of processing bulk InP samples (contact application, electrical measurements) and vacuum-depositing CdS films on bulk InP and other substrates. The first MO-CVD InP films to be sent to Stanford for experimental use were expected to be p-type Zn-doped epitaxial films grown on $p^+ \text{InP:Zn}$ single-crystal substrates. However, films in the appropriate doping range had not become available during this reporting period. It is anticipated that such films will be prepared and supplied to Stanford early in the next quarter.

3. SUMMARY AND CONCLUSIONS

An existing MO-CVD reactor system used in a previous DoE-sponsored contract has been modified and upgraded for use in preparing InP films on various low-cost substrates for solar cell applications. The system was modified to provide for deposition of GaAs films by the MO-CVD process, so that intermediate layers of that material can be deposited on the low-cost substrates prior to InP film deposition if desired, as an integral part of the cell structure growth sequence. After the initial InP deposition experiments were undertaken, the quartz deposition chamber was redesigned to incorporate a larger ground joint, to accommodate larger-diameter susceptors and facilitate chamber assembly, disassembly, and cleaning procedures. The typical InP deposition rate profile for the conditions used in experiments during the first quarter exhibited a useful deposition region approximately 1 cm in diameter, centrally located on the susceptor of ~ 5 cm diameter, in which the film growth rate was relatively uniform for deposition in the temperature range 650-725°C and for growth rates in the order of 0.1 $\mu\text{m}/\text{min}$.

Undoped epitaxial InP films were deposited on single-crystal InP substrates of the (100) and (111A) orientations at temperatures in the range 625-725°C to establish the nature and concentration of the background doping in the reactor system as it was used early in the program, and to evaluate the overall quality of the InP material being produced at that time. It was found that the background provided n-type doping in otherwise undoped epitaxial films in this temperature range, on both crystallographic orientations. For

films grown on (100)-oriented substrates the background donor doping was temperature-activated, with an activation energy of ~ 1.8 eV, indicating that the doping mechanism may have been surface-controlled rather than gas-transport-controlled.

Initial experiments in the preparation of Zn-doped p-type InP epitaxial layers on single-crystal InP (100) and (111A) substrates, using a dopant source of DEZn already on hand at the start of the program and maintained at 0°C during deposition, were successful in producing p-type films only when relatively high (≥ 10 ccpm) flow rates of the DEZn- H_2 mixtures were used. Even then the films had relatively rough surfaces and generally poor morphology.

However, after introduction of the modified deposition chamber and new (and somewhat larger) susceptors, and especially after replacement of the old DEZn source by a new source tank ordered specifically for this program, much improved results were achieved. It was found that active Zn doping concentrations (i.e., measured hole concentrations) in the 10^{17} cm^{-3} range could be produced in epitaxial films on (100), (111A), and (111B) InP substrates in the $715\text{--}730^{\circ}\text{C}$ range by "proportioning" the flow of the DEZn- H_2 mixture to obtain sufficiently dilute Zn concentrations in the deposition chamber. The observed uptake of Zn impurity in these films again varied with crystallographic orientation, as had also been observed in earlier studies; Zn is apparently most readily incorporated into the films of (111A) orientation and least readily in the (111B) films, with the (100) films intermediate between the two.

Attempts to utilize an existing premixed source tank of H_2 doped with dimethylzinc (DMZn) as a dopant for producing p-type InP layers in the MO-CVD reactor were thwarted when it was found that the active dopant compound had become completely depleted in the tank during the long period in which the tank had been stored at Rockwell. Whatever the cause, this development prompted indefinite postponement of plans to test DMZn-in- H_2 as a source of the Zn dopant in this program.

Characterization of the epitaxial InP films grown by MO-CVD during this quarter was accomplished by x-ray and electron diffraction analyses, examination of film surfaces and sample cross-sections in the SEM, and measurement of transport properties by van der Pauw measurements of the Hall effect. Some difficulties have been encountered in delineating the film-substrate interface in making film thickness determinations in cross-sections of InP films grown on InP substrates, especially when the film is undoped. Various etches were tested for the purpose of staining the region in a discriminatory way, and although some success has been achieved the result is still somewhat variable. Fortunately, this problem is not expected to persist when InP films are deposited on dissimilar substrate materials later in the program.

The device fabrication and characterization work, to be carried out primarily at Stanford University and to involve the preparation and evaluation of CdS/InP (and possibly ITO/InP) heterojunction solar cell structures, has been delayed; this has been caused partly by a delay in completion of subcontract negotiations and partly by the lack of suitably doped p-type InP

films prepared by MO-CVD at Rockwell. Preliminary experimental work has been under way at Stanford, however, using bulk InP crystals. Also, the two problems mentioned above have both now been resolved, so the device work is expected to commence in the coming quarter.

Based on the work of the first quarter, as summarized above, it appears that considerable additional effort must be devoted to establishing reproducible procedures for achieving the desired Zn doping concentrations in epitaxial InP films of various crystallographic orientations and, subsequently, in polycrystalline InP films on various low-cost substrate materials. This may require further exploration of background doping under various experimental conditions and the establishing of working doping curves for Zn at two or more InP deposition temperatures. In addition, suitable InP film samples must be prepared for use by Stanford in carrying out the necessary investigations of the CdS/InP heterojunction device structure.

Identification and preparation of the low-cost substrates to be used in the initial deposition experiments with polycrystalline InP films must also be undertaken. Based on the results obtained in the previous DoE-sponsored contract work (Ref. 1) and on the importance of obtaining satisfactory ohmic contact to the back side of polycrystalline InP solar cells on low-cost substrate materials, it is expected that early emphasis will be placed on the use of substrates of Mo or Al in bulk sheet form and of these same metals as thin layers previously deposited by suitable methods onto low-cost insulating materials such as glass and alumina. A number of samples of commercially available materials in bulk sheet form are still available from the supplies

obtained for the previous contract work and will be used in the early part of the current contract. These will be employed primarily as substrates for deposition of various intermediate layers - notably GaAs deposited in situ by MO-CVD and Ge deposited by CVD (GeH_4 pyrolysis) in a separate reactor system - for use as InP growth surfaces. The availability of additional low-cost substrate materials will also be investigated - an activity that will continue throughout the program but at a relatively low level of intensity since other aspects of the work require the principal emphasis.

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4. PLANS FOR NEXT QUARTER

The planned activities for the second quarter include the following:

TASK I Continue investigation of preparation of Zn-doped p-type InP films by MO-CVD, and extend the study to include Cd (from dimethylcadmium) as an acceptor impurity; begin deposition of doped and undoped InP polycrystalline films by MO-CVD on various suitable substrates; begin preparation of partial-coverage InP films for investigation of film nucleation and early-stage growth phenomena on selected substrates subjected to various special surface treatments; prepare films of appropriate properties for use at Stanford (in Task III); seek new candidate substrate materials having required properties.

Task II Continue routine characterization of structural and electrical properties of InP films on various substrates; begin investigation of properties of crystal grains and grain boundaries in polycrystalline InP films grown on low-cost substrates; prepare Au Schottky-barrier devices on p-type InP films of suitable doping concentration, as means for evaluating film properties.

Task III Establish optimized CdS vacuum-deposition procedures for use with MO-CVD InP films; prepare CdS/InP heterojunction solar cell structures and characterize resulting photovoltaic properties; establish basis for continued investigation of IT0/InP heterostructure for solar cell applications.

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5. REFERENCES

1. "Thin Polycrystalline Films of Indium Phosphide on Low-cost Substrates," DoE Contract No. EY-76-C-04-3727, administered by Albuquerque Operations Office, U.S. Department of Energy.
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3. M. S. Abrahams and C. J. Buiochi, J. Appl. Phys. 36, 2855 (1965).