InP SINGLE-JUNCTION CONCENTRATOR CELL

MASTER

SEMI-ANNUAL REPORT
(October 1, 1980 to March 31, 1981)

Contract SERI XZ-0-9354

for
Solar Energy Research Institute

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

by

Paul E. Gregory

Varian Associates, Inc.
Solid State Laboratory
Palo Alto, CA 94303

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
I. INTRODUCTION	1
II. InP MATERIAL	2
A. Chloride Transport VPE	2
B. Ion-Implanted InP for Solar Cells	3
C. Organometallic VPE Growth of InP	3
III. INVESTIGATIONS OF GLASS BONDING	9
IV. BACK CONTACT TECHNOLOGY	11
V. COMPUTER MODEL OF InP SOLAR CELL	12
VI. OHMIC CONTACT STUDIES	19
A. Method of Analysis	19
B. Ohmic Contact Results	24
VII. FRONT-CONTACTED InP CELL RESULTS	28
A. Ion-Implanted Cell	28
B. Cl-VPE InP Cell	31
VIII. REFERENCES	39

I. INTRODUCTION

The purpose of this work is to develop a glass-sealed back-contacted InP or InGaAsP solar cell for use in concentrator systems. This cell is expected to have a greatly improved efficiency over that of conventional AlGaAs/GaAs cells because of the back contact scheme and because no window layer, such as the AlGaAs layer in AlGaAs/GaAs cells, is required.

By contacting both n and p layers from the back of the cell, obscuration of the front of the cell is greatly reduced or eliminated. Furthermore, the contact grid can be made thicker than is possible on front-contacted cells, thus reducing the series resistance in the grids. The back-contacted cell will be fabricated by depositing the active epitaxial layers on an InP substrate, bonding the front side of the structure to glass, and then by removing the substrate. Contact to the front (emitter) layer will be made by etching through the base layer in the contact areas.

The AlGaAs window layer on AlGaAs/GaAs cells is required to reduce the high surface recombination velocity that would otherwise be present at a GaAs/air interface. Unfortunately, the AlGaAs layer also absorbs some of the incident light, thereby reducing the cell efficiency somewhat. However, the surface recombination velocity of n-InP is lower than that of GaAs by as much as four orders of magnitude.¹ Thus no window layer is needed to passivate the InP surface. The surface recombination velocity at the interface between InP and a low-temperature pyrolytic SiO₂ is also low.²

Work to be performed in developing this cell includes growing the InP epitaxial layers needed for cells and test structures, developing a model to be used in optimizing the cell structure, measurement of InP parameters necessary for use in the model, and developing the glass-bonding and back-contacting scheme. Accomplishments in these areas will be discussed below.

II. InP MATERIALS GROWTH

Epitaxial InP layers for the program are being produced by chloride transport vapor phase epitaxy (Cl-VPE). Work is also in progress to develop InP growth by organometallic VPE (OM-VPE). There has also been some effort at producing InP cells by ion implantation. The work in each of these areas is described in more detail below.

A. Chloride Transport VPE

Most of the InP epitaxial growth for this program will be produced by Cl-VPE. Two Cl-VPE reactors have been used for the program thus far. Each reactor uses a slightly different form of Cl-VPE. In the first reactor to be used for this project, PCl_3 is passed over an In melt to form a P-saturated In melt and InCl vapor. InCl and PCl_3 flow down the reactor tube to the InP substrate. The reactor temperature at the substrate is held at a value at which the InCl and PCl_3 react to form InP at the substrate.

In the second reactor, phosphorus is introduced via PH_3 instead of PCl_3 . HCl vapor flows over the In melt to form InCl. The PH_3 is introduced downstream from the In melt and reacts with the InCl to deposit InP on the InP substrate. The second reactor also has a Ga melt and AsH_3 gas supply, so that $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$ quaternary alloys can be grown. The quaternary alloys will be required for the glass-bonded back-contacted InP cell. The second reactor is also more versatile than the first reactor in that it has both p- and n-type dopants, while the first reactor only has p-type dopants. The disadvantage of the second reactor is that it has primarily been used for quaternary growths in the past, and the conditions for good InP growth had not been established. About 10 runs were required before InP growths with a smooth surface were obtained. However, as will be discussed below in the section on VPE-grown cells, more work is necessary to achieve uniformity in layer thickness.

At the start of this program, Cl-VPE InP growths were begun in the first reactor discussed above. Several p-type InP layers were grown on n-InP, and the best of these were used for ohmic contact evaluation. Unfortunately, the engineer who was being trained to do the Cl-VPE work quit to take another job soon after he had learned to run the reactor. In the last part of this reporting period, S. B. Hyder began producing VPE InP layers for this project in the second reactor discussed above. InP growths are now being made routinely, providing ample material for the program. Solar cells are now being processed. Results from the first cell through this processing are discussed in the experimental results section below.

B. Ion-Implanted InP for Solar Cells

During the period in which VPE InP was not available, ion implantation was investigated as an interim technique for providing InP for cells and test structures. One ion-implanted cell was fabricated, and four additional wafers have been implanted but not yet processed. When VPE material became available again, priority was given to working with the VPE material. It is expected that the VPE material quality will be better than that of the implanted material and, of course, VPE growth will be required for the glass-bonded structure. However, the wafers that have been implanted will be processed as time permits.

C. Organometallic VPE Growth of InP

Another alternative to Cl-VPE InP which has been explored is growth by OM-VPE. OM-VPE growth of AlGaAs/GaAs solar cells has been very successful. Relatively large-area wafers (2 wafers, each 2 x 2 inches per run) are grown routinely, with good electrical properties and good control over layer thicknesses and composition. Three OM-VPE reactors are in use and growths of AlGaInAs and GaAsSb⁴ alloys have been developed

in addition to growth of the AlGaAs/GaAs system. In light of this success with other materials, it is desirable to develop the OM-VPE growth of InP. An immediate advantage of the OM-VPE system is that it would permit the use of larger-area wafers. The Cl-VPE system in use is limited to wafers no more than $1/2 \times 3/4$ inch.

The growth of InP by OM-VPE has been reported,^{5,6} but it has not been extensively developed. Therefore, it has been necessary to do some preliminary studies to determine the best method for OM-VPE InP growth.

Three approaches to OM-VPE InP growth have been tried in our work: direct growth from trimethylphosphene (TMP) and trimethylindium (TMin), growth from the solid phase adduct⁶ of TMP and TMin, and growth from the gas phase adduct of TMP and TMin. Growth of InP appears to have been achieved from the latter two approaches, but the growth rate has not yet been determined.

The first approach to InP growth that was tried was to use TMP and TMin in approximately 10:1 ratio at growth temperatures of 600 and 660°C. No InP growth occurred in either run, but In was deposited in droplets on the substrate surface. However, it is possible that some atmospheric contamination was trapped in the sliding-cover susceptor when these growth runs were made, and it may have interfered with the growth. After these runs had been made, it was learned how to prevent trapped atmospheric contamination.

The second approach to OM-VPE growth was more successful. In this approach, the adduct⁶ $(\text{CH}_3)_3\text{In-P}(\text{CH}_3)_3$ is first formed by mixing TMP and TMin at 77°K, warming to 300°K, and then purification by sublimation under an excess of TMP. The adduct thus formed is a white solid. Growth was made with 1:5 flow ratios of H_2 over the adduct and PH_3 , with the substrate at 525°C. The resulting growth rate appeared to be very small, as determined by cleaving and staining. However, it has since

been determined that the staining was not delineating the grown layer properly; the actual growth rate is thus not known.

The third approach bypasses the rather tedious and time-consuming process of synthesizing the solid adduct. Instead, the gas phase adduct is directly synthesized by premixing TMP and TMI_n in a mixing chamber attached to the reactor, and the resulting adduct flows directly into the reactor. A number of growth runs have been made with the gas phase adduct, and the substrate at 580°C. As with the second approach, the growth rate has not yet been determined due to a failure of the cleaving and staining process to delineate the grown layer. The InP growths so far have been undoped, and the staining etch apparently delineates a difference in doping type.

Although the direct evidence of InP growth from a cleaved cross section has not been obtained, there is other convincing evidence that InP growth has indeed been achieved. Figure 1 shows the photoluminescence (PL) spectrum from sample 30M-86. This sample was grown by the gas-phase adduct method, on a Fe-doped semi-insulating InP substrate. The PL signal of Fig. 1 is strong, and the peak at 1.407 eV is characteristic of InP at the measurement temperature of 77°K. No PL signal would be expected from the Fe-doped substrate, and none was found when a PL measurement was attempted from the back side of the sample 30M-86, even with ten times the incident laser power and twice the monochromator slit opening used in the measurement of Fig. 1. Thus the PL measurement is strong evidence that InP growth did take place on the front of the wafer.

Another piece of evidence in favor of InP growth is point contact measurements. The I-V curve for two point probes placed on the surface of 30M-86 showed the back-to-back diode characteristic expected from a semiconductor of moderate resistivity. Probes placed on the back side of 30M-86 showed only the very slight leakage and no diode characteristic expected from Fe-doped InP.

Fig. 1 Photoluminescence spectrum of OM-VPE InP sample 30M-86.

Figure 2 is a photomicrograph of the surface of a typical OM-VPE InP growth at a magnification of 1400. Striations characteristic of VPE growth are just visible in Fig. 2, and provide further evidence that InP growth took place. The rounded objects at the center of mounds are probably In droplets resulting from slight surface decomposition of the substrate prior to growth. A sliding graphite cover was designed for the susceptor to cover the wafer and prevent this surface decomposition. A similar sliding cover, made from quartz, is successfully used to prevent surface decomposition in Cl-VPE InP growth.³ The graphite cover was used for all of the OM-VPE InP growths discussed here. It greatly reduced the surface decomposition, but it did not eliminate it, as Fig. 2 shows. The sliding cover protects the InP surface by holding phosphorus vapor that sublimates from the InP surface, thus keeping a P overpressure at the InP surface. The graphite cover may afford less protection than quartz because the graphite is fairly porous, and may absorb some of the P. Quartz cannot be substituted for graphite in our OM-VPE reactor, since the substrate holder is also an rf susceptor. A new graphite sliding-cover susceptor has been designed and fabricated which will give additional protection to the InP surface by incorporating a source of additional P to increase the P overpressure over the InP substrate. This new susceptor will be used for InP growths in the future.

Another improvement to the OM-VPE reactor is the addition of new plumbing which will allow In and P sources to be permanently installed. Previously it has been necessary to replace other sources with the In and P sources, a time-consuming process which also increases the chances of introducing contamination into the reactor. The new plumbing will greatly simplify the preparations prior to making InP growth runs. More OM-VPE InP growth runs will be made in the near future. The results to date indicate that progress should be rapid.

—
10 micron

Fig. 2 Photomicrograph of the surface of a typical OM-VPE InP growth.

III. INVESTIGATIONS OF GLASS BONDING

Some investigations of glass bonding from the glass-bonded back-contacted InP solar cell have been made. Thermocompression bonding to 7056 glass for photocathodes is well established at Varian,⁷ and is in use in several photocathode products produced by Varian. It is expected that this thermocompression bonding will work well with the InP solar cell. Nevertheless, it was decided to explore several alternative bonding techniques in case any offers advantages over the thermocompression bonding. These investigations are being pursued in parallel with work performed under Sandia contract 74-3195, which requires a technique for bonding a high-bandgap AlGaAs cell to glass.

Bonding by use of polyimide as an adhesive has been investigated. It does not appear to be usable as a direct bonding agent because of outgassing during imidizing.

An approach that looks more promising is the use of Teflon FEP sheet as the bonding agent. The FET is placed between the cell and glass, and the assembly is heated until the FEP softens at ~350°C.

Another technique which appears promising is electrostatic bonding. With electrostatic bonding, it is possible to bond semiconductors or metals to glass at temperatures far below the glass-softening temperature by applying an electrostatic field to the glass. In the tests we have performed so far, the semiconductor to be bonded is placed face up on a heater block, and the glass is placed on top of it. The block is heated to 350-600°C in air, and a wire probe held at 600-1200 volts $\pm$ with respect to the heater block is touched to the center of the glass. No pressure is otherwise applied to the glass. The bonding is visible as it progresses across the glass, expelling air from between the semiconductor and glass. Electrostatic bonding has worked well with silicon test pieces, but preliminary tests with InP have been unsuccessful. Bonds appeared to form, but the InP and glass separated upon cooling.

We know of no reason why electrostatic bonding should not work with InP, so more effort will be directed toward establishing the conditions needed to achieve electrostatic bonding. The next attempt at bonding will be made with InP which has a CVD-deposited SiO_2 layer on it.

Electrostatic bonding may offer two advantages over thermocompression bonding. The fact that little or no pressure is required for electrostatic bonding may mean that the InP is strained less during the bonding process. Secondly, since electrostatic bonding can take place at lower temperatures than thermocompression bonding, a wider variety of types of glass can be used with the electrostatic bonding. For example, Corning 7740 glass appears to be attractive because of its good thermal expansion match to InP (4.5×10^{-6} for InP, 3.25×10^{-6} for 7740 glass). The softening temperature of 7740 glass is probably too high for it to be thermocompression bonded to InP, but electrostatic bonding may be possible.

IV. BACK CONTACT TECHNOLOGY

Detailed development of the back contact technology for the glass-bonded InP cell will be deferred until more results from front-contacted InP cells are available. We have already developed similar contacting systems for the high voltage cell (SERI contract XS-0-9010-0) and for the metal-interconnected multijunction cell (SERI contract XP-9-8081-1), and we expect to apply much of that technology to the development of the back-contacted InP cell.

V. COMPUTER MODEL OF InP SOLAR CELL

A computer-based model has been developed for the InP solar cell. The model will be of use in designing InP cells and interpreting measurements from those cells. Results of measurements on InP cells and test structures will in turn be used to modify parameters used in the model.

The InP solar cell model is based on similar modeling done at Varian for other solar cells, in particular for the high-voltage GaAs cell developed under SERI contract 9010-10. The model first solves for the quantum yield spectrum for the cell, and uses that to get the generated short-circuit current for the AM1 spectrum. The cell output I-V curve is then found by use of a transmission line model. The transmission line model is shown in Fig. 3. This model is for a radial grid pattern of the type that is used for the front-contacted InP test cells, as well as our standard AlGaAs/GaAs cell. The model can easily be modified for a linear grid pattern of the type that will be used for the back-contacted cell.

In the model of Fig. 3, the cell is broken into equal area concentric rings. The number of rings used involves a tradeoff between accuracy and calculation time. Most of the modeling done so far uses 15 rings; the results do not seem to be very sensitive to the number of rings used. The current generators supply IL , the short-circuit current generated in each ring. For uniform illumination, IL is the same for each ring, since the rings have equal area. R_c contains both the contact resistance and the emitter sheet resistance, while the resistors R_g contain the grid series resistance. The cell I-V characteristic is generated by working out from the cell center. A voltage is picked for node 1, the node connecting R_{c1} and R_{g1} , and a solution is found for the current through R_{g1} . This solution must be found numerically because of the nonlinear diode characteristic. The voltage at node 2 is found by subtracting the voltage drop across R_{g1} from the voltage at node 1. The

Fig. 3 Transmission line circuit for solar cell model.

current through R_{g2} is then found, and the process repeated until the voltage and current at the cell terminals are found. Then another voltage is picked for node 1, the transmission line model is again solved to give another point, and so on, until the cell I-V characteristic has been generated. With the cell divided into 15 rings, an I-V curve containing ~30 points is generated in 3-5 minutes with the model running on an HP-9845 computer.

The model assumes three active layers: two emitter layers and a base layer. The inclusion of two emitter layers provides for a high/low doped emitter structure to aid in reducing the effects of surface recombination. Parameters which are entered into the model are doping and thickness for each of the three active layers; grid line spacing, width, thickness, and resistivity; front and back surface recombination velocity; contact resistivity, and diffusion length for each layer. Any one of these parameters can be chosen as the independent variable. Cell efficiency, short circuit current, open circuit voltage, and fill factor are calculated for several values of the independent variable. Figure 4 shows output from a sample run, where efficiency is plotted as a function of base layer doping, with the other parameters listed at the top of the layer.

Mobility and resistivity data for past InP growths in this laboratory were compiled for use in the InP solar cell model; the data is shown in Figs. 5 and 6. The solid lines are polynomial fits to the data; the polynomial fits were used in the model.

The model uses GaAs diffusion length values as an approximation of the InP diffusion lengths, or it allows a value for the diffusion length to be specified. Diffusion lengths for InP will be measured from InP p-n junctions by electron beam-induced current (EBIC) or by fitting the quantum yield curve. When diffusion lengths for a range of InP dopings have been measured, they will be incorporated into the model. Other

NUMBER OF RINGS 15
 AREA OF CELL = .563 cm²
 Fst LAYER THICKNESS = .05 micron
 Sec LAYER THICKNESS = 1.00 micron
 Thd LAYER THICKNESS = 5.00 micron
 GRID LINE SPACING = 100.0 micron
 GRID LINE WIDTH = 7.00 micron
 GRID LINE THICKNESS = 2.00 micron
 TOP LAYER IS N TYPE
 SOLAR CONCENTRATION = 400
 DOPING OF Fst LAYER = 1.00E+19
 DOPING OF Sec LAYER = 1.00E+16
 DOPING OF Thd LAYER = 1.00E+19
 CONTACT RESISTANCE = 1.00E-04
 GRID LINE RESISTIVITY = 2.00E-06
 Sfront = 10000
 Sback = 10000

Fig. 4 Typical results from InP cell model.

Fig. 5 Mobility versus doping for InP layers grown at Varian.

Fig. 6 Resistivity versus doping for InP layers grown at Varian.

parameters which need to be measured for InP are surface recombination velocity, the voltage for transition from generation/recombination to diffusion-domination of the junction characteristics, and ohmic contact resistivity.

The model has been run with a wide range of parameter values. The results suggest an optimum structure having an n-on-p structure with a first emitter layer about 0.05 μm thick, doped $\sim 1 \times 10^{19} \text{ cm}^{-3}$, a second emitter layer $1 \pm 0.5 \mu\text{m}$ thick doped 1×10^{16} - $1 \times 10^{17} \text{ cm}^{-3}$, and a base layer $\sim 5 \times 10^{17} \text{ cm}^{-3}$. Initial VPE cell growths are being made with these parameters.

VI. OHMIC CONTACT STUDIES

A. Method of Analysis

The resistance measured between two contacts on a semiconductor surface consists of a component from the semiconductor sheet resistance, and a component for the resistance between the contact and the semiconductor surface. The sheet resistance can be separated from the contact resistance by measuring the resistance between a pair of contact pads as a function of spacing between the pads, and extrapolating the resistance to zero spacing.

A circuit model for an ohmic contact is shown in Fig. 7a. It consists of distributed elements corresponding to the substrate sheet resistivity, R_s , and the contact resistance R_c . The active layer is assumed to be electrically isolated from the substrate, so that current flow is essentially one dimensional.

By inspection, the current loss along the substrate is

$$\frac{dI}{dx} = - \frac{V(x)}{R_c} \quad (1)$$

The voltage drop under the contact is

$$\frac{dV}{dx} = - R_s I(x) \quad (2)$$

Differentiating (2) and substituting (1) gives the potential distribution under the contact,

$$\frac{d^2V}{dx^2} - \frac{R_s}{R_c} V = 0 \quad (3)$$

Fig. 7(a) Model for ohmic contact analysis.

Fig. 7(b) Potential distribution from model.

The solution with a potential V_0 at the contact edge is

$$V(x) = V_0 \exp - \left[\frac{x}{L_T} \right] \quad (4)$$

with

$$L_T = \sqrt{\frac{R_C}{R_S}} \quad (5)$$

Figure 7b shows this distribution. In the channel, before the contact, the potential drops linearly. Under the contact, the potential drops exponentially as Eq. (4). As an example, for $R_C = 4 \times 10^{-4}$ ohm-cm² and $R_S = 40$ ohms, L_T is 30 microns. This is considerably shorter than the pad width.

Finally, it is seen that the intercept of the straight line with the x axis lies at $x = L_T$. This can be shown by realizing that the channel current is

$$I = \left(\frac{V_a - V_0}{R_S} \right) \frac{Z}{L} = \frac{MZ}{R_S} \quad (6)$$

where V_a is the applied voltage, Z the width, and L the length of the channel, and $M = dV/dx$ in the channel. The contact current equals the channel current. The contact current is found from integrating (1):

$$I = \frac{Z}{R_C} \int_0^\infty V(x) dx = \frac{Z V_0}{R_C} \int_0^\infty e^{-\frac{x}{L_T}} dx = \frac{Z L_T V_0}{R_C} \quad (7)$$

Comparison of (6) and (7) yields $M = V_0/L_T$, so that the x intercept lies at $x = L_T$.

This technique can be used to determine both R_C and R_S . We take a number of contact patterns fabricated on the same wafer, of identical geometry except that the channel length L is varied from pattern to pattern. Plotting the channel resistance as a function of channel length in effect gives a plot of the $x > 0$ region of Fig. 7b. The intercept at $R = R_0$, from Eq. (7) gives

$$R_0 = \frac{V_0}{I} = \frac{\sqrt{R_C R_S}}{Z} \quad (8)$$

The slope of the plot gives the active layer sheet resistivity from

$$m = \frac{d R_{ch}}{d L} = \frac{\rho_S}{t Z} = \frac{R_S}{Z} \quad (9)$$

where R_{ch} is the channel resistance, t the thickness, and ρ_S the layer resistivity. Combining (8) and (9) gives the contact resistance,

$$R_C = \frac{Z R_0^2}{m} \quad (10)$$

(Note: For R_0 measured from a symmetric pattern of two pads separated by a channel, R_C calculated from q. (10) is twice the true contact resistance.)

Figure 8a shows one section of the ohmic contact test pattern that has been used thus far in this program. It is produced from a mask originally used for source-drain pads for FETs. Each test pattern consists of 11 sets of 3 pads of the type shown in Fig. 8a, with the pad spacing ranging from ~1 to ~20 microns. There is a twelfth pad with zero spacing to measure the probe and lead resistance. Resistance is measured across either or both adjacent pads for all eleven sets of pads by probing the pads under a microscope. The individual spacings must then be measured under high power and the data then analyzed as described above.

Fig. 8(a) One set of pads from present ohmic contact pattern. Spacing g varies from $\sim 1 \mu\text{m}$ to $\sim 20 \mu\text{m}$ in 11 sets of pads.

Fig. 8(b) Improved ohmic contact test pattern. Spacing g varies from 10 to 85 μm . Other dimensions are in μm .

Several shortcomings have become evident with this ohmic contact test pattern, so a new pattern has been designed which, it is hoped, will be an improvement. Most of the difficulties from the old pattern result from the narrow spacings of the majority of the pairs of pads; 9 of the 11 pad pairs have a spacing below 10 microns. The narrow spacings are very hard to measure accurately, and the resulting uncertainty in spacing is a major source of error in the measurements. The lift-off process used to define the pads leaves the pads with a edge roughness that is an appreciable fraction of the pad spacing for the narrowest spacings; this also contributes to uncertainty in the measurements. The most narrowly spaced pads are often shorted out due to incomplete lift-off. Furthermore, the ohmic contact analysis discussed above implicitly assumes that the pad-to-pad spacing is large compared to the layer thickness; This assumption is clearly violated for the narrower spacings in the test pattern.

The new pattern overcomes these problems by having wider spacings, varying from 10 to 85 microns. The pads have also been increased in size to minimize end effects and to make probing of the pads faster and easier. A new probe station has been purchased which gives better control over the probes, also making the probing easier. The mask for the new test pattern is being fabricated. When it is received, it is planned to order a probe card that will probe all pads at once. It is expected that the new test pattern and probe card will allow ohmic contact resistance measurements to be performed much faster and with greater accuracy than has been previously possible.

B. Ohmic Contact Results

Ohmic contact experiments thus far have concentrated on testing the contacts that we use on standard AlGaAs/GaAs cells: 300 Å Au/125 Å Mg/ 300 Å Au/1000 Å Ti-W/1500 Å Au for p-type material and 100 Å Au/250 Å Sn/ 100 Å Au/1000 Å Ti-W/5000 Å Au for n-type. It would be most

convenient for processing if the same contacts are adequate for both InP and AlGaAs/GaAs cells. However, we plan to investigate several other contact systems for InP, as well. In particular, Ag only, Ag/Sn/Ag, Ag/Mg/Ag, and Au-Ge/Ni/Au are interesting possibilities.

Two ohmic contact tests have been run on p-InP using Cl-VPE-grown p-InP on n-type substrates. Arrays of ohmic contact patterns (of the type shown in Fig. 8a) were photolithographically defined on the wafers. The wafers were then cleaved into smaller pieces, with one test pattern per piece. Each piece was annealed at a different temperature. Annealing was carried out in H_2 atmosphere on a graphite strip heater. Pad-to-pad resistances and spacings were then measured. Contact resistivity and sheet resistance were then calculated for each piece using a least-squares fit to the pad-to-pad resistance values, plotted versus pad-to-pad spacing.

Pieces of the first wafer, V-7, were annealed for one minute each at temperatures from 375 to 500°C. Unfortunately, the lift-off used to define the patterns was incomplete, leaving metal bridges joining many of the pads. There was also severe blistering on many of the pads following anneals over 425°C. Because of these problems, it was not possible to get meaningful values for contact resistance from this wafer.

Pieces of the second wafer, V-8, were used for one-minute anneals for temperatures 300-420°C, and 10-minute anneals for temperatures 300-380°C. The lift-off was good for sample V-8, and blistering of contacts was not a problem. Figure 9 shows the results of the ohmic contact test on sample V-8. Unfortunately, the data is rather scattered. There is a possible trend towards a minimum contact resistance for 1-minute anneals at ~340°C.

Fig. 9 Contact resistivity vs anneal temperature for contacts to p-InP.

The error bars of Fig. 9 reflect different fits to the measured points; they are not intended to indicate the total error. Several factors which may contribute to the scatter in the data are the difficulties with the ohmic contact test pattern discussed above, nonuniformities in the epitaxial layer thickness or doping, and nonuniform heating across the wafer during anneal. Nonuniform thickness of the epitaxial layer is especially likely for pieces cleaved from the edge of the wafer. Under the microscope, the epitaxial layer appeared to fade away near those edges. Future work will try to understand which of these problems are significant so that they can be avoided.

One qualitative study has been made of Au/Sn/Au (with no Ti-W diffusion barrier) on n-type InP. The study was only qualitative because bulk n-type material was used; the ohmic contact analysis described above does not apply to contacts on a thick piece of material, so no contact resistivity values were obtained. Ohmic contact patterns were defined and the wafer cleaved into individual pieces, as before. The pieces were annealed for 90 seconds each, under H_2 , at temperatures from 340-400°C, at 10°C intervals. Pad-to-pad resistance was measured for 4 pairs of pads on each piece. The minimum average resistance was found for anneals in the range 360-380°C. This temperature range is being used as a guide for annealing the contacts on the InP cells being fabricated.

It was decided to defer further ohmic contact measurements until the improved contact mask is received.

VII. FRONT-CONTACTED InP CELL RESULTS

A. Ion-Implanted Cell

A front-contacted InP cell has been fabricated, using ion implantation to form the p-n junction. The substrate was Zn doped to $\sim 5 \times 10^{17} \text{ cm}^{-3}$. It was given a double implant with doses of $2 \times 10^{13} \text{ cm}^{-2}$ at 170 KeV and $8 \times 10^{13} \text{ cm}^{-2}$ at 50 KeV. The doping profile expected from this implantation is shown in Fig. 10, assuming complete activation of implanted ions, no dopant diffusion, and the projected range statistics of Ref. 9.

The implanted wafer was annealed at 750°C for 20 minutes; annealing at 750°C has been reported to give good activation for Si implanted into InP.¹⁰ The anneal was capless (i.e., no SiO_2 or Si_3N_4 protective layer was used); the surface was protected by performing the anneal in an epitaxial reactor that provides a phosphorus overpressure to prevent InP surface decomposition. It was necessary to cleave the wafer into pieces approximately .3 x .3 inches to fit the reactor.

A pattern of 20-mil dots was photolithographically defined on the front surface, instead of a grid pattern. The front contacts were 100 Å Au/250 Å Sn/100 Å Au and the back was 300 Å Au/125 Å Mg/300 Å Au.

The quantum yield measured from this cell (Cell I-1) is shown in Fig. 11. The dashed line is reflectance, and the solid line is internal quantum yield (i.e., the yield corrected for sample reflectance). The structure in the reflectance curve was caused by interference in the SiO_2 layer which was used in the front contact photolithography, and had not been removed at the time of the quantum yield measurements. The yield of Fig. 2 was measured before the contacts were annealed, but no improvement in yield was seen following annealing at 360°C for 90 seconds.

Si IMPLANTED IN InP

IMPLANT ENERGY: 50 KEV FLUENCE: $8.00E+013 \text{ CM}^{-2}$

plus 170 keV

$2E+13 \text{ cm}^{-2}$

approximate
substrate
doping

Fig. 10 Ion implant profile for InP cell I-1.

InP I-1 (NO CONTACT ANNEAL, SiO₂)
MEASURED MARCH 12, 1981

Fig. 11 Quantum yield for ion-implanted InP cell I-1.

The quantum yield is quite disappointing, having a low peak value, and falling off badly at higher photon energies. The computer InP model, with a doping profile modeling Fig. 10, gives a quantum yield curve similar to that of Fig. 11, if the diffusion length in the implanted layer is very low, ~ 0.1 micron. This low diffusion length could be caused by damage from the ion implantation. An attempt will be made to measure the diffusion length with EBIC.

The I-V curve for cell I-1 exhibits a high series resistance. This fact is also consistent with poor material quality in the implanted region.

Four more InP wafers were implanted. Two changes were made in the implantations which are intended to increase the diffusion length compared to that of cell I-1, discussed above. First, the wafers were held at 200°C during implant, rather than at room temperature as for cell I-1. Ion implantation in InP at elevated temperatures has been reported to cause less damage than implantation at room temperature.^{11,12} Second, the implants were made with S, which is a faster diffusing dopant than the Si used for cell I-1. It is intended to drive the junction deeper, beyond the implanted (and damaged) layer during diffusion. The four wafers were each given a dose of $5 \times 10^{14} \text{ cm}^{-2}$, but each was implanted at a different energy: 25, 40, 80 and 120 keV, respectively. Annealing and processing of these wafers will proceed in the next contract period.

B. C1-VPE InP Cell

An InP cell, number Q38-12, has been fabricated by C1-VPE and more C1-VPE cells are in processing. The substrate is p-type, $5 \times 10^{17} \text{ cm}^{-3}$. The emitter layer is nominally $1\text{-}\mu\text{m}$ thick, doped $\sim 1 \times 10^{16} \text{ cm}^{-3}$ n-type. An attempt was made to give the emitter a very thin n^+ layer at the surface by shutting off all gas flows except the n-dopant flow at the

conclusion of growth. It is not known if an n^+ layer resulted from this technique.

A 1/3-inch radial grid pattern that is used for our AlGaAs/GaAs cells was defined on the front of the cell. Front and back contacts were annealed together at 350°C for 90 seconds before the front contacts were Au plated. After the cell had been cut to size by scribing and cleaving, the I-V characteristic indicated that one contact was still not ohmic, so the cell was annealed again, at 390°C for 90 seconds. The I-V curve was satisfactory after this second anneal.

The I-V curve for cell Q38-12, under one-sun illumination in a solar simulator, is shown in Fig. 12. This I-V is much better than that of the ion-implanted cell, with no indication of severe series resistance. Both the open circuit voltage and short circuit current are lower than would be expected for a high-efficiency cell, however. The open circuit voltage will probably increase with concentration. The low short circuit current is the result of thickness nonuniformities in the emitter layer, as will be discussed below.

The quantum yield for Q38-12 is shown in Fig. 13. The internal quantum yield (yield corrected for cell reflectance) is plotted. The cell reflectance is shown by the dashed curve. The yield shown in Fig. 13 is for a cell with no antireflection coating, and with the SiO_2 used for photolithography removed.

The quantum yield of Fig. 13 is quite low. To aid in understanding this result, an electron beam-induced current measurement (EBIC)^{13,14} was made on an edge scrap from cell Q38-12. The EBIC scan is shown in Fig. 14. The cell surface is to the left, with the junction at the lowest point on the curve. Measuring the slope of the linear portions of the logarithm of the EBIC signal gives diffusion lengths about 1 μm in the n-type emitter and 5.7 in the p-type base region. These estimates

Fig. 12 I-V for InP cell Q38-12 under solar simulator at ~1 sun.
Zero is at white dot at upper left. Vertical scale:
100 mV/div. Horizontal scale: 2 mA/div.

InP cell Q 38-12 (SiO2 off)
MEASURED April 23, 1981

Fig. 13 Quantum yield of Cl-VPE InP cell Q38-12.

10 MICRONS

Fig. 14 EBIC measurement on InP cell Q38-12.

of diffusion length represent a lower limit on the true diffusion length, since it is known that EBIC can underestimate the diffusion length, especially for incident electron beam energies below 50 KeV.¹⁴ The EBIC measurement of Fig. 14 was made with a 30-keV beam energy, the highest available energy on our SEM.

The most surprising feature of Fig. 14 is that it indicates a junction depth of 8.8 μm . A cleaved and stained section taken from an area near that from which the EBIC scan was measured showed a junction depth of 5.8-7.2 μm , depending on how one defined the junction edge. Both measurements show a junction depth much greater than the expected $\sim 1 \mu\text{m}$. This discrepancy was explained by a closer examination of a VPE InP growth that followed Q38-12. It was found that the thickness of the epitaxial layer varied by about a factor of two across the wafer. In addition to that variation, there were broad hillocks on the wafer surface $\sim 6 \mu\text{m}$ high. There were hillocks scattered over the entire surface of Q38-12. Figure 15 shows the surface of Q38-12 at about 200X. There are small hillocks over most of the surface, and some larger ones (the rectangular objects). It is possible that the EBIC measurement was made at a hillock, which would account for the larger than expected junction depth. Also, the EBIC scan was made near the wafer edge, where the epitaxial thickness variation would most likely be most severe.

The presence of hillocks partly explains the low quantum yield. The hillocks are so thick that they effectively shadow the cell. The variation in epitaxial layer thickness also would be expected to lower the quantum yield. The thinnest part of the layer, about 1 μm , is about the same as the diffusion length from the EBIC scan. Thus the thicker areas would have lower quantum yield.

Figure 15 illustrates one other factor which contributes to low quantum yield: the grid lines are too wide. They are 14- μm wide, about twice the intended width. Either the Au plating was too thick or the

Fig. 15 Photomicrograph of the center of InP cell Q38-12.

photolithography produced thick lines, because the hillocks kept the mask from contacting the wafer. The quantum yield of Fig. 13 is corrected for specular reflection, but not for grid obscuration. The grid plating is fairly rough, and the lines are rounded, so light reflected from the grid does not fall on the detector used to measure light reflected from the cell.

Two more processing steps are intended for Q38-12. First, a low-temperature pyrolytic SiO_2 layer will be applied to the surface as an antireflection coating, and to see if there is any evidence for a change in surface recombination. Second, the cell will be packaged so it can be tested under high concentration.

More Cl-VPE InP wafers have been grown and are being processed, and more wafers will be grown. VPE growth parameters are being adjusted in an attempt to reduce the number of hillocks and improve the thickness control. The surface of Q38-12 shows much improvement over that of the first few InP growths with this Cl-VPE reactor, so further improvement can be anticipated. Also, the emitter doping will be gradually increased to see what effect that has on cell performance.

VIII. REFERENCES

1. H. C. Casey, Jr. and E. Buehler, Appl. Phys. Lett. 30, 247 (1977).
2. L. Messick, D. L. Lile and A. R. Clawson, Appl. Phys. Lett. 32, 494 (1978).
3. S. B. Hyder, Proc. 1980 NATO InP Workshop, Hanscom AFB, MA, 375 (June 1980).
4. C. B. Cooper III, M. J. Ludowise, V. Aebi and R. L. Moon, J. Elec. Matls. 9, 299 (1980).
5. H. M. Manasevit and W. I. Simpson, J. Electrochem. Soc. 120, 135 (1973).
6. K. W. Benz, H. Remz, J. Weidlein and M. H. Pilkuhn, J. Electron. Matls. 10, 185 (1981).
7. G. A. Antypas and J. Edgecumbe, Appl. Phys. Lett. 26, 371 (1975).
8. D. W. Egelkrout and W. E. Horne, NASA Conf. Pub. 2169, Space Photovoltaic Research and Technology 1980, NASA Lewis Research Ctr, OH, 317 (October 1980).
9. J. F. Gibbons, W. S. Johnson and S. W. Mylroie, Projected Range Statistics (Dowden, Hutchinson & Ross, Inc., Stroudsboro, PA, 1975).
10. D. E. Davies, J. P. Lorenzo and M. L. Deare, Appl. Phys. Lett. 31, 256 (1977).

11. J. P. Donnelly and C. E. Hurwitz, Appl. Phys. Lett. 31, 418 (1977).
12. D. E. Davies, J. J. Comer, J. P. Lorenzo and T. G. Ryan, Appl. Phys. Lett. 35, 192 (1979).
13. D. B. Wittry and D. F. Kyser, J. Appl. Phys. 36, 1387 (1965).
14. Zh. I. Alperov, V. M. Andreev, V. I. Murygin and V. I. Stremin, Sov. Phys.-Semiconductors 3, 1234 (1970).