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"Amorphous-Si Solar Cells"

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1st Quarterly Progress Report

1 January - 31 March 1979

DOE/ET/23034--T3

Prepared By:

Institute of Energy Conversion
University of Delaware
Newark, DE 19711

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Principal Investigator

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1st Quarterly Progress Report

(January-March 1979)

Abstract

This report describes the effort at University of Delaware during the first three months of a Department of Energy sponsored a-Si program. The objectives of the program are to study and improve photovoltaic properties of plasma-deposited a-Si and model a-Si devices with a view towards improving device design. The major accomplishments during the quarter are:

1. A capacitively-coupled, RF-induced plasma-system for depositing a-Si has been built and a-Si films have been deposited from SiH_4 decomposition.
2. The resistivity, doping and photoconductivity studies of a-Si have been started. a-Si films are highly photoconductive and can be doped relatively easily by AsH_3 .
3. A device-analysis program to model quantum efficiency of a-Si devices has been written. The program has been used to study the performance of a-Si devices as a function of diffusion lengths, junction layer widths etc. The program shows the importance of using extremely narrow junction widths and back-surface reflection of light. The program can also simulate light-trapping in a-Si cells, and it is shown that even partial light-trapping can lead to ~20% improvement in efficiency, a significant increase for films with small diffusion lengths.

I. Introduction

a-Si is a promising photovoltaic material. It offers ease of deposition, control of electronic properties, a direct bandgap and simplicity of device preparation.^(1,2) However, present day cells are limited to low efficiency (~6%).⁽³⁾ The objectives of the a-Si program at the University of Delaware are to understand the material properties of a-Si and to model a-Si devices so as to evolve an optimized device design. To this end, four distinct tasks will be undertaken in collaboration with our subcontractors, the University of Chicago. These four tasks are:

- (1) Material growth
- (2) Measurement of photovoltaic-related material properties
- (3) Device preparation
- (4) Device design and loss-minimization analysis.

During the first quarter, Tasks (1), (2) and (4) were started at Delaware. The work during the first quarter has proceeded under a limited, (30% of requested monthly budget) pre-contract-award authority from DOE. As a result, our subcontractors, University of Chicago, will not start work until the second quarter. This report describes the progress achieved during the first quarter.

II. Material Growth System

We have designed and installed a plasma deposition system which can be used to deposit a-Si films from SiH_4 on a variety of substrates.⁽⁴⁾ The system consists of a capacitively-coupled, parallel-plate RF plasma decomposition chamber which is pumped by a mechanical pump. The system is fed by a Plasma-Therm 75W 13.56 MHz generator coupled through an impedance matching network. Gas flow into the system is controlled by Matheson flowmeters (610 tubes) and precision NRS-1 valve cartridges. A schematic diagram of the deposition system is shown in Fig. 1, the gas flow system is schematically shown in Fig. 2 and the impedance network is shown in Fig. 3. The pressure in the system is monitored by a MKS Baratron 222 AHS capacitance manometer gauge. The pressure in the chamber can be controlled by throttling the vacuum valve.

The substrates can be mounted either on the RF side (cathodic films) or on the ground electrode (anodic films). The RF electrode acquires a negative bias with respect to the ground electrode, and the bias can be controlled by controlling plate geometries. Thus, both cathodic and anodic films can be grown in one run. The substrates are heated by a cartridge heater controlled by a Eurotherm temperature controller/SCR unit.

For the sake of safety, the outflow from the vacuum system is mixed with N_2 (4l/min) at the pump outlet, giving a dilution rate of 100:1. Typical flow rate of SiH_4 : Ar or SiH_4 :He mixtures are 10-100 sccm. The N_2 mixture is passed through a stainless tube, heated to $\sim 1000^\circ\text{C}$, decomposing SiH_4 (and dopants) and passing on only diluted H_2 , He and Ar.

The results of Tsai and Fritzsche⁽⁵⁾ and Knights et al⁽⁶⁾ indicate that cathodic films have significantly lower spin densities, do not form

A-SI DEPOSITION SYSTEM (RF)

Fig. 1

Fig. 2
Schematic of Gas Mixing System

Legend: R : Pressure Regulator/Outlet Valve DV: Diaphragm Valve
 EFM: Electronic Mass-Flow Meter SCV: Solenoid Cut-Off Valve
 MFM: Manual Mass-Flow Meter
 NV : Needle Valve

Fig. 3

Impedance Matching Network

columnar structure, have better photoluminescent properties and can be grown at faster rates than anodic or grounded films. Hence, we have concentrated on growing cathodic films. The films were grown by decomposing SiH_4 :Ar (10% SiH_4) mixtures. The typical power levels are 0.1 - 0.5 w/cm^2 . The typical target area is 2.5 cm x 2.5 cm. The substrates can be either Corning 7059 glass, or Molybdenum strips, or glass coated with $\sim 1000 \text{ \AA}$ of Molybdenum. The substrates are held down by a target ring (Fig. 4) which defines the film area.

Some film-growth rates are shown in Fig. 5. Typical RF-induced bias voltages were -40 to -100V. The pressures were in 300-500 μm range. The films were examined under a SEM, and were found to be generally free of pinholes or structure. This is consistent with the observation of Knights et al⁽⁶⁾ about smoothness and lack of structure in cathodic films. Typical growth temperatures were $\sim 350 - 400 \text{ C}$.

Preliminary doping studies on the films were started using AsH_3 and PH_3 as n-dopants. For ease of control, AsH_3 or PH_3 were diluted in Argon or H_2 . Typical dilution rates were 1000 ppm - 1% AsH_3 or PH_3 in H_2 or Ar. The use of low dilution, premixed gas mixtures makes control of dopant levels in the 50 ppm - 10,000 ppm range relatively simple. Simple manual flowmeters can be used to control dopant levels. The results of the doping experiments are described in Sec. III.

Fig.4
Target Ring

IEC79020

IEC79030

Fig. 5

Deposition Rate of a-Si:H Films

III. Material Properties

1. Absorption Coefficient. A typical absorption vs. photon energy curve is shown in Fig. 6. The extrapolated bandgap, obtained by fitting $\sqrt{\alpha h\nu}$ vs. $h\nu$ to the data, is 1.7 eV, in the range obtained by other workers. ⁽⁷⁾

2. Resistivity. The resistivity of undoped a-Si:H films was measured using a 4-point probe technique. 4 parallel evaporated Mg lines 1.8 cm long spaced 2.5 mm apart, were used to measure the resistivity of the films. The resistance was measured using a Keithley nanoamp. current source and a Keithley electrometer to measure voltage. The undoped films had very high resistivity ($\sim 10^{10}$ Ω -cm). By including 1000 ppm PH_3 in the gas mixture, the resistivity was reduced to 5×10^3 Ω -cm. This value of doped-film resistivity is in the range reported by other workers in the field. ⁽¹⁾

3. Photoconductivity. Preliminary measurements on photoconductivity of the films were done by using an ELH lamp calibrated to 100 mW/cm² intensity to simulate AM1 sunlight. The conductivity of both doped and undoped films increased upon simulated AM1 radiation. Photoconductivity values of approximately $\rho = 10^3 - 10^4$ Ω -cm were obtained in the a-Si films. More detailed measurements are in progress. The preliminary measurements indicate a majority carrier $\mu\tau$ product of 10^{-3} cm²/V, somewhat larger than reported by Spear. ⁽¹⁾

4. Photo-induced change in conductivity. In parallel with the results of Staebler and Wronski, ⁽⁸⁾ our films also show a photo-induced increase in dark resistivity. We shall be examining this phenomenon in greater detail during the next quarter.

Fig. 6

Absorption Coefficient of a-Si:H

 $T_S = 350^\circ\text{C}$

5. Photoluminescence. Knights and his coworkers⁽⁹⁾ have shown that photoluminescence is a powerful tool for analyzing defect states. Our a-Si:H films show a strong photoluminescence signal. The photoluminescence was measured using the apparatus shown schematically in Fig. 7. Basically, the apparatus consists of 2W Argon laser, which excited the sample held on a cold-finger or in a liquid N₂ dewar. The light from the sample is collected by a condensing lens, and focused onto a Si detector. For higher accuracy, the laser light was chopped and the signal measured using a PAR HR-8 lock-in amplifier. The laser light was blocked off by a blocking filter and a monochrometer.

A typical spectrum of photoluminescence from a-Si:H is shown in Fig. 8. The strong peak at 1.2 eV agrees with the previous results of Engemann and Fisher,⁽¹⁰⁾ Pankove and Carlson⁽¹¹⁾ and Street et al.⁽¹²⁾

Thus, our preliminary measurements indicate that our material properties are similar to the best properties observed by previous workers. This indicates that our material preparation technique is under control and will produce material which can be used for devices in the later stages of this program.

Fig. 7

IEC7902I

Fig. 8

IV. Device Design

In order to produce the highest efficiency devices, the device design must take full advantage of material properties. The design should be based on realistic and achievable material properties, and must include a consideration of technological and processing limitations.

Cell design and cell development goals must be arrived at from a systematic examination of material properties and device construction technology.

During this quarter, we have started a device analysis program which addressed these considerations.

(1) Study of Quantum Efficiency

Quantum efficiency is defined as collected electron (hole) per incident photon. Internal quantum efficiency (quantum efficiency calculated after subtracting reflection losses) as a function of wavelength of light provides valuable information on diffusion lengths, surface recombination etc. (14,15) We have computed the quantum efficiency for a-Si:H solar cells, using the field-free transport equations of Rothwarf et al. (16) The equations have been modified to include effects of back surface reflection and multiple light-passes through the material due to light trapping.

The basic device structure is shown in Fig. 9. It consists of a p^+n junction cell, with a thin p^+ layer. The light is incident on the junction side. The light may be reflected back into the cell from the back surface (metallic substrate) with a reflection coefficient R_2 . Part of this reflected light may be trapped in the cell by being reflected back into the cell at the front surface. The coefficient for this front reflection back into

LIGHT TRAPPING IN SOLAR CELL

Fig. 9

Basic Diode Structure

the cell is denoted R_1 .

The basic transport equations are: (16)

$$QE_1 = \frac{\alpha L_1}{\alpha^2 L_1^2 - 1} [S_1 + \alpha D_1 - \exp(-\alpha W_1) \{ \frac{D_1}{L_1} (\sinh(\frac{W_1}{L_1}) + \alpha L_1 \cosh(\frac{W_1}{L_1})) + S_1 (\alpha L_1 \sinh(\frac{W_1}{L_1}) + \cosh(\frac{W_1}{L_1})) \}] / [S_1 \sinh(\frac{W_1}{L_1}) + \cosh(\frac{W_1}{L_1})] \quad (1)$$

$$QE_2 = \frac{\alpha L_2}{\alpha^2 L_2^2 - 1} e^{-\alpha W_1} [\exp(-\alpha W_2) (S_2 - \alpha D_2) + \frac{D_2}{L_2} \{ \alpha L_2 \cosh(\frac{W_2}{L_2}) \} + S_2 \{ \alpha L_2 \sinh(\frac{W_2}{L_2}) - \cosh(\frac{W_2}{L_2}) \}] / [S_2 \sinh(\frac{W_2}{L_2}) + \frac{D_2}{L_2} \cosh(\frac{W_2}{L_2})] \quad (2)$$

where the symbols have the following meanings:

QE_1 is the quantum efficiency of layer 1 (junction layer)

QE_2 is the quantum efficiency of layer 2 (base layer)

α is the absorption coefficient

S_1, S_2 are the front and back surface recombination velocities.

W_1, W_2 are the thicknesses of the junction and base layers.

L_1, L_2 are the effective diffusion lengths of the junction and base layer

D_1, D_2 are the diffusion coefficients of the junction and base layer.

Note that we have used effective diffusion lengths L_1, L_2 . The effective diffusion lengths include any field-assisted transport. To a first approximation, a cell with a depletion layer width, W_d , would have an effective diffusion length $L_2^{\text{eff}} = W_d + L_2^{\text{actual}}$. Thus, for a $0.3 \mu\text{m}$ depletion layer and $0.1 \mu\text{m}$ diffusion length, the effective diffusion length, to a first approximation, is $0.4 \mu\text{m}$. A more accurate expression will be studied later in the program.

In the presence of back-reflection (R_2) and partial light-trapping (R_1), these expressions are modified as follows:

$$QE_3 = QE_1]_{1-2} \quad (3)$$

where 1 - 2 means that all the parameters with subscript 1 are replaced by parameters with subscript 2, i.e. L_1 is replaced by L_2 etc.

$$QE_4 = QE_2]_{2-1} \quad (4)$$

Then, from simple geometrical considerations,

$$QE_1(R_1, R_2) = \frac{1}{1 - R_1 R_2 \exp(-2\alpha w)} [QE_1 + R_2 \exp(-\alpha w) \cdot QE_4] \quad (5)$$

$$QE_2(R_1, R_2) = \frac{1}{1 - R_1 R_2 \exp(-2\alpha w)} [QE_2 + R_2 \exp(-\alpha w) \cdot QE_3] \quad (6)$$

where $QE_1(R_1, R_2)$ and $QE_2(R_1, R_2)$ are the total quantum efficiencies of the two layers under multiple internal reflections.

The total quantum efficiency, QE^T , is:

$$QE^T = QE_1(R_1, R_2) + QE_2(R_1, R_2) \quad (7)$$

The short circuit current J_{SC} is given by:

$$J_{SC}(\lambda) = q N_{ph}(\lambda) QE^T(\lambda) \cdot d\lambda \quad (8)$$

where $N_{ph}(\lambda) \cdot d\lambda$ is the number of AM1 photons in an interval $d\lambda$ around λ .

The average quantum efficiency, $QE(Ave)$, is given by:

$$QE(Ave) = \frac{\int_{\lambda_1}^{\lambda_2} N_{ph}(\lambda) QE^T(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} N_{ph}(\lambda) d\lambda} \quad (9)$$

where λ_1 is the short wavelength limit of the solar spectrum and λ_2 is the limit of the solar cell response (e.g. for a-Si, $\lambda_1 = 0.3 \mu m$ and $\lambda_2 = 0.8 \mu m$).

The expressions (1) - (9) allow us to study the sensitivity of quantum efficiency of a-Si solar cells to variations in cell parameters and to multiple internal reflections.

The results of this first analysis are shown in Fig. 10-16. The absorption curve given by Carlson et al⁽²⁾ was used in the computations.

Figure 10 shows the influence of base layer diffusion length L_2 on quantum efficiency. The junction layer is assumed to be very thin (300 Å). It is

Fig. 10
Influence of Base Layer Diffusion Length
On Quantum Efficiency

apparent from Fig. 10 that increasing L_2 merely increases QE in the red and infrared regions of the spectrum, and the increase tends to saturate. The corresponding J_{SC} vs L_2 curve is shown in Fig. 11, which shows that the current effectively saturates for $L_2 > 1 \mu\text{m}$, and there is no significant benefit to increasing L_2 beyond $1 \mu\text{m}$.

The influence of back-surface reflection and light-trapping are shown in Fig. 12. With a 85% back surface reflection (achievable with many metals), the quantum efficiency increases significantly for the typical small effective L_2 ($0.3 \mu\text{m}$) found in a-Si:H devices. Upon the inclusion of 50% internal reflection at the front surface (as might be achieved by using a diffuse back reflector), the red region quantum efficiency increases further. The corresponding J_{SC} is shown in Fig. 11, as the broken-curve. It is obvious from Fig. 11 that back surface reflection and partial light trapping are very important in achieving high J_{SC} . Even for small effective diffusion lengths ($0.3 \mu\text{m}$), partial light trapping can give $J = 14\text{--}15 \text{ mA/cm}^2$ at 100 mW/cm^2 AM1 input, after allowing a 10% front reflection loss. Thus, 15 mA/cm^2 is a realistic goal for $J_{\text{operating}}$, when the depletion layer width $\sim 0.3 \mu\text{m}$.

The influence of varying the junction layer thickness is shown in Fig. 13. It is assumed that $L_1 = W_1$, and that $S_1 L_1 / D_1 < 1$, which assures small surface recombination. It is seen that as W_1 increases, there is a significant loss in quantum efficiency in the blue region, resulting in a loss in J_{SC} , as shown in Fig. 13. An increase in L_1 to $2W_1$ prevents the loss in J_{SC} , as shown in Fig. 14. Thus, there is no benefit to increasing the junction layer thickness beyond $500 \text{ \AA}$, unless a high diffusion length can also be achieved. This is primarily a consequence

Fig. 11

Influence of Light Trapping on Current

Fig. 12

AM1 PHOTON SPECTRUM

INTERNAL QUANTUM EFFICIENCY
($L_2 = 0.3$ MICRONS)

IEC79033

Fig. 13

Influence of Junction Thickness on Quantum Efficiency

IEC79034

Fig. 14

of the very high absorption constant of a-Si in the blue region of the spectrum. To maintain the quantum efficiency in the blue region with increased junction width, will require an increased diffusion length in the junction region and a decrease in absorption. Both of these can be achieved by using a graded band-gap illustrated in Fig. 15. The graded-gap provides a built-in field which sweeps electrons towards the junction, and also reduces absorption at any wavelength compared to a lower-gap a-Si:H. This structure will be simulated in detail during the next quarter.

The influence of varying the base layer thickness is shown in Fig. 16, where we plot J_{SC} vs. base-layer thickness for a varying W_2 . Fig. 16 also shows a curve showing the influence of W_2 on J_{SC} when back-surface reflection R_2 is present. We note from Fig. 16 that an increase in W_2 does not significantly increase J_{SC} , and may actually reduce J_{SC} when back-surface reflection is important. Thus, it does not pay to increase W_2 beyond $2L_2$. i.e. $W_2 < 2L_2$. This result is obvious. An increase in W_2 leads to increased photon absorption in the region beyond L_2 . Most of the holes generated by photons in this "beyond-the-frontier" region are lost by recombination. Instead, when back-surface reflection is present, it is better to absorb photons in a "useful" region of the base layer, i.e. within a distance L_2 of the junction. Thus, with back-surface reflection, should be certainly less than $2L_2$ and preferably of the same order as L_2 .

To summarize, the detailed analysis of Quantum Efficiency of a-Si solar cells, has revealed the following conclusions.

- (i) Back surface reflection and light trapping can increase J by ~20% for small effective diffusion lengths ($\sim 0.3 \mu\text{m}$). This translates into a 20% increase in efficiency.
- (ii) Effective diffusion lengths of $0.3 - 0.5 \mu\text{m}$ are adequate to assure reasonable J . A current of 15 mA/cm^2 at AM1, after allowing 10% light

Fig. 15

A Graded-Bandgap Junction Cell

IEC79035

Fig. 16

loss due to front surface reflection and grid shadowing, is a realistic goal and can be achieved with $L_2 \approx 0.3 - 0.5 \mu\text{m}$. A further increase in diffusion length leads only to marginal increases in current.

(iii) The junction layer must be kept very thin ($\sim 300 \text{ \AA}$), or there may be a significant loss in blue region quantum efficiency. A method for increasing quantum efficiency in the blue region would be to use graded junction layers where bandgap increases towards the surface. This device would provide both increased quantum efficiency due to a built-in field and decreased absorption.

(iv) The width of the base layer should be comparable to the diffusion length. This consideration is particularly important for back-reflection-assisted and light-trapped solar cells.

These conclusions are preliminary and more detailed computations, including built-in field effects, will be performed during the next quarter.

(2) Fill Factor

In addition to the parameter affecting the fill factor of all solar cells there are two considerations specifically important when analyzing fill factors of a-Si:H cells. These are:

- (i) Series Resistance
- (ii) Field-dependence of the light generated current.

During this quarter, we have analyzed (i), and during the next quarter, we shall analyze (ii).

(i) Series Resistance:

Two types of series resistance effects are important. These are:

- (a) Bulk or base layer series resistance
- (b) Sheet resistance of junction layer

The base layer resistance effect is usually negligible in a-Si:H solar cells because the base layer is thin ($< 1 \mu\text{m}$) and also because

photoconductivity assures a $\rho < 10^4 \Omega\text{-cm}$. The effect of the base layer series resistance on power loss is given by:

$$\% \text{ Power loss} = \frac{I^2 R_{\text{base}}}{\text{Power generated}} \times 100 \quad (10)$$

Using our notation

$$\% P_{\text{loss}} = \frac{J^2 \rho_2 W_2}{P_{\text{gen}}} \cdot 100 \quad (11)$$

For $10^4 \Omega\text{-cm}$, $1 \mu\text{m}$ wide base, with $J = 15 \text{ mA/cm}^2$ and $P_{\text{gen}} = 10 \text{ mW/cm}^2$

$$\% P_{\text{loss}} = 2.2\%, \text{ entirely negligible.}$$

which is a negligible loss.

This is a worst-case calculation. Typically, of course, $W_2 = 0.5 \mu\text{m}$ and photoconductivity is $\sim 10^3 \Omega\text{-cm}$, making base layer resistance entirely negligible.

The sheet-resistance effect, on the other hand, is quite significant for a p^+n junction cell. This is because although the junction layer will be of low resistivity ($\sim 10^2 \Omega\text{cm}$) it is so thin ($\sim 300 - 500 \text{ \AA}$) that the junction sheet resistance loss given by (15),

$$\% P_{\text{loss}} = 100 \cdot \frac{1}{12} \frac{J^2 R_s s^2}{P_a} \quad (12)$$

where R_s is sheet resistance

s is the separation of grids

P_a is the power per unit area.

For a $500 \text{ \AA}$ thick junction layer $R_s = 2 \times 10^7 \Omega/\square$.

Hence, even for 10% loss, $s \leq 16 \mu\text{m}$. This implies that the width of the grid line, which must be $< 10\%$ of grid separation, has to be $\sim 1.6 \mu\text{m}$ which is not feasible in practice for large area cells.

Thus, the sheet resistance in p^+n junction cells is going to be a major problem.

A possible solution to this problem is to use a transparent conducting oxide layer on top of a-Si to provide a low sheet resistance. This can be done by using Indium-Tin Oxide (ITO). ITO can be highly transparent ($\sim 95\%$) with a low sheet resistivity ($< 1000 \Omega/\square$).⁽¹⁸⁾

Using $R_s = 1000 \Omega/\square$, equation (12) gives us $S = 1 \text{ mm}$ for a power loss of only 2%. A grid separation of 1 mm allows us the use of a grid width of $50 \mu\text{m}$ to produce only 5% transmission loss. Thus, using ITO reduces power loss, light transmission loss and allows us to use simple techniques such as screen-printing for putting down grids.

(3) Open-circuit Voltage

V_{OC} depends upon the type of cell (MIS, Schottky, pn junctions etc.). Schottky devices are likely to have the smallest V_{OC} , because of the high dark current from a Schottky metal. MIS cells are likely to have a smaller dark current due to preferential blocking of majority-current tunnelling,⁽¹⁹⁾ and hence higher V_{OC} , but they suffer from being extremely sensitive to insulating layer thickness, and hence are difficult to make in production. If an ideal junction can be made a p^+n cell appears to have the potential for the best V_{OC} . Present junction in a-Si suffer from excessive space-charge recombination,⁽²⁰⁾ leading to non-ideal $I(V)$ and low V_{OC} . It is believed that these problems can be overcome by appropriate design and technology. If successful

this would result in an a-Si cell with an open circuit voltage of ~1 V.

The results of Williams on electrochemical a-Si cells⁽²¹⁾ have shown that a high V_{OC} (1.2 V) can be achieved in a-Si:H in that system. The reported V_{OC} in present devices is therefore thought to be limited by extrinsic effects such as surface states or excessive junction recombination and should not be taken to represent a fundamental limit. A goal of a 1 Volt open circuit voltage is seen as quite reasonable and is not precluded for any known fundamental reason.

V. Conclusions

During the first quarter, we have achieved the following objectives:

1. Material Growth: A material deposition system has been designed and set-up, and has been used to grow undoped and n-doped a-Si:H films. The system allows significant flexibility in deposition parameters.
2. Material Characterization: Preliminary characterization of materials has been started. Apparatus to measure photoconductivity, conductivity, and photoluminescence have been set up. The films grown in our system have high photoconductivity, can be easily doped and exhibit significant photoluminescence. The program now has the ability to produce films which appear to match the state of the art achieved by other groups in the field.
3. Device Design. A program to analyze device design of a-Si solar cells has been started. Detailed solutions of transport equations have been generated and design criteria have been established for junction and base layer widths, design of grids and V_{OC} . The significant influence of back-surface reflection and multiple-internal-reflections on increasing J_{SC} has been verified by computer simulations. A design goal of $J = 15 \text{ mA/cm}^2$ has been established. An innovative structure for reducing the loss of quantum efficiency for short-wavelength photons in the p^+ region of the cell has been identified.

VI. Plans for Next Quarter

During the next quarter, we plan to undertake the following activities:

- (1) Material Growth. We expect to study the doping efficiency of a-Si by doping with AsH_3 and B_2H_6 . We shall study doping as a function of deposition parameters.
- (2) Material Characterization. We expect to study the influence of preparation conditions on intergap state densities by the Field Effect experiments. We also plan to set up vacuum conductivity measurements so as to exclude water vapor and to determine activation energies by measuring conductivity vs. temperature for doped and undoped films. We also plan to set up apparatus for measuring mobility and diffusion lengths.
- (3) Device Design. The device analysis program will be modified to study innovative structures with built-in fields, graded bandgaps, and stacked-junction cells. The analysis of fill factor will be extended to include field (and hence light) dependence of operating current. Realistic design goals on J_{SC} and FF in these optimized cells will be arrived at.

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