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PHASE I OF THE AUTOMATED ARRAY ASSEMBLY TASK
OF THE LOW COST SILICON SOLAR ARRAY PROJECT

Motorola Report No. 2258/6. Technical Quarterly Report No. 5

By
M. Coleman
R. Pryor

September 1977

MASTER

Work Performed Under Contract No. NAS-7-100-954363

Motorola Incorporated
Semiconductor Group
Phoenix, Arizona

U.S. Department of Energy

Solar Energy

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Project No. 2258

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1.0 SUMMARY STATEMENT

Studies on definition of solar cell design and solar cell variables, selection of processes and process sequences, definition of process variables, relationships between primary process variables and cell variables, selection of evaluation techniques, and primary variable evaluation have progressed during this period.

Studies reported here include solar cell design and solar cell variables, a technical and economic discussion of limits on solar cell dimensions, the presentation of five process sequences, the definition of individual process steps of which each of the five process sequences will be comprised, the definition of primary process variables, and tables showing the qualitative interrelationships between processing and solar cell variables.

2.0 INTRODUCTION

Phase I of the Automated Array Assembly Task, LSSA Project, is concerned with a comprehensive assessment of the improvements in existing technology that may be needed to develop, within a period of no more than 10 years, an industrial capability for low cost, mass production of very durable silicon solar photovoltaic modules (and arrays).

This portion of the Phase I study involves the definition and analysis of control parameters of individual process steps as well as the integrated process sequence, and of the effects of these control parameters on the final solar cell (and module) structure, performance, and cost effectiveness.

3.0 TECHNICAL DISCUSSION

3.1 DEFINITION OF SOLAR CELL AND SOLAR CELL VARIABLES

Studies of control variables for solar cell manufacturing must start with a definition of the desired solar cell structure, which can be related to the properties of the cell, and, in turn, related to desired process results for given process steps and sequences. Ultimately, it is desired to relate solar cell variables (and their variations) to process variables (and their control limits).

The solar cell which is considered for these studies is a silicon solar cell with a shallow ($<1\mu$) metallurgical P-N junction, a back surface high-low junction (enhancement layer), and patterned front and full back contact metallizations. The cell also has an antireflection coating covering a texture-etched front surface.

The solar cell may be characterized by a variety of operational and diagnostic variables, which can be classed as electrical, physical, or mechanical, and primary or secondary. Ultimate observation of the cell will be based upon the operational variables, while control of these operational variables will rely heavily upon control of the diagnostic variables.

Operational variables are those properties of the solar cell which are observed when the cell is either being interconnected and encapsulated or when the cell is functioning in test or service.

Cell variables which affect the operational variables are classed as diagnostic variables. Changes in operational variable values for a solar cell should be capable of correlation with changes in one or more of the diagnostic variables.

Table 1 lists the primary operational variables and Table 2 lists the primary diagnostic variables for solar cells.

In addition to the quantitatively defined variables shown in Tables 1 and 2, an additional primary cell variable is the degree of front surface (and/or back surface) deviation from flatness due either to surface texturing or to warpage. Attempts will be made to quantify this factor.

Two other primary variables are of major importance to the LSSA Project, but are considered beyond the scope of this study. First, potential interfacial interactions within the module (such as surface chemical reactions, interfacial migration, electrochemical processes, and thermal stressing) are too complex to analyze adequately in the period of time devoted to this study. Second, reliability of a solar cell in its environment as part of a module is a subject which would require long term testing of appreciable numbers of modules. In both cases, wide variations in module design and construction by the solar module industry make current studies of entire configurations premature.

TABLE 1
PRIMARY SOLAR CELL OPERATIONAL VARIABLES

Short Circuit Current, I_{sc} (T)
Open Circuit Voltage, V_{oc} (T)
Maximum Power, P_{max} (T)
Cell Conversion Efficiency, η (T)
Voltage at Maximum Power, $V_{p_{max}}$ (T)
Current at Maximum Power, $I_{p_{max}}$ (T)
Fill Factor, FF (T) = $P_{max} / (I_{sc})(V_{oc})$
Cell Series Resistance, R_{series}
Cell Shunt Resistance, R_{shunt}
Cell Thickness, t
Cell Diameter, D
Cell Length, L
Cell Width, W
Cell Area, A
Cell P-N Junction Area, A_j
Metallization Area, A_M
Metallization Coverage, $A_M/A_j \times 100\%$
Metallization Pattern Dimensions, t_M, W_M, l_M
Contact Placement

TABLE 2
PRIMARY SOLAR CELL DIAGNOSTIC VARIABLES

P-N Junction Depth, x_j
Metallization Penetration Depth, x_m
P-N Junction Layer Sheet Resistivity, ρ_{sj}
Metal Sheet Resistivity, ρ_{sm} (for each metallization width)
Back Surface (enhancement layer) Sheet Resistivity, $\rho_{s \text{ back}}$
Back Surface High-Low Junction Depth, $x_{j \text{ back}}$
Substrate Bulk Resistivity, ρ
Front Surface Dopant Concentration, C_s
Back Surface Dopant Concentration, $C_{s \text{ back}}$
Dopant Profiles, $C(x)$; $C_{\text{back}}(x)$.
Crystal Orientation, (hkl)
Dislocation Density N_d
Spectral Response of Short Circuit Current, $I_{SC}(\lambda)$
Minority Carrier Lifetime, τ
Diode Dark Characteristics, I vs V
Surface Recombination Velocity, S
Front Surface Reflectivity, $R(\lambda)$
Base Thickness, w_B
Metal Adherence, M
Uniformity (of Operational and Diagnostic Variables over the Surface of the solar cell.)

3.2 DISCUSSION OF MAXIMUM SOLAR CELL SIZE

The lateral dimensions of silicon sheets to be fabricated into solar cells and encapsulated into modules are of major importance with respect to sheet (or crystal) growth, solar cell efficiency, manufacturing costs, and inter-connection and encapsulation costs.

The current and power generated from a solar cell are area dependent. Accordingly, to a first approximation, it may be assumed that the same power can be generated from several large cells having the same total silicon area as many small cells. Upon closer examination, however, it can be seen that trade-offs exist as the cell size increases, placing a limit on the size of a solar cell from the standpoints of both cell output efficiency and cost effectiveness.

The primary argument for increasing solar cell size is to achieve economies resulting from minimizing the number of units being handled through a processing sequence and the number of cells to be interconnected prior to encapsulation. This argument assumes that the equipment utilized can process units at approximately the same rate, regardless of size, and that equipment for handling different sizes of sheets costs nearly the same amount. A great deal of support for this argument can be made by analogy to the overall semiconductor industry. There, wafer size has increased from early diameters of 0.7 inch through 2 and 3 inches and up to 5 and 6 inches in the course of less than fifteen years. This dramatic size increase is justified primarily on the basis of handling economy. There are many recorded cases of severe yield reduction when larger wafers were introduced into various semiconductor device and integrated circuit product lines. Specific process R&D effort has gone a long way towards improving yields with larger silicon wafers. However, even though the yield in terms of good units per unit area of silicon may be lower for larger wafers than for smaller ones, the increased throughput

and reduction of edge loss combine to make the use of larger wafers economically favorable.

For solar cells, however, other factors limit the maximum favorable size of the device. As cell size increases, processing equipment must become more sophisticated (and expensive) in order to achieve control and uniformity over the larger area, ultimately offsetting economies of handling. If any yield-loss mechanisms which are fundamentally area dependent exist, larger cells would mean higher costs due to increased yield loss. Conceptually, at least, future technology advances could minimize the effects of these limitations.

The most important limiting factor on large solar cell dimensions is a fundamental design consideration: increased cell size ultimately requires increased percentage metallization coverage in order to maintain a constant voltage drop per unit area in an effort to maximize cell output power. Increased metal coverage, however, results in shadowing of active cell area and reducing available power generating area. Hence, active area must be traded against increased series resistance, in order to achieve an optimal design to minimize efficiency loss as cell size increases.

While these (and similar) arguments have been widely discussed, few attempts have been made to put the limitations on cell size on a quantitative basis. An approach is presented in the following discussion to quantify these design trade-offs and to evaluate the cost effectiveness of increased solar cell sizes.

3.2.1 EFFICIENCY CONSIDERATIONS

In order to study quantitative effects of solar cell dimensions on performance and cost effectiveness, it is necessary to establish a reference model for a solar cell on which calculations and discussion can be based. Such

a reference cell has been formulated, having parameters which are of high quality. It is recognized that volume production may result in solar cells of lower quality than the model. The high quality cell has been chosen, however, to identify optimum conditions for determining cell dimensions and cost effectiveness, recognizing that in practice a cell of this quality must have smaller dimensions than calculated here. Restated, this approach identifies maximum desirable dimensions, with actual dimensions perhaps being smaller.

This approach, in turn, will place an upper limit on the size goals that the sheet and crystal growers may utilize in defining their processes.

The reference solar cell is chosen to be an ideal silicon diode with electrical contacts at the perimeter. When exposed to a solar insolation (air mass one) of $100\text{mW}/\text{cm}^2$, the reference cell is assumed to have a generation current density, J_{gen} , of $40.0\text{mA}/\text{cm}^2$ and an open circuit voltage, V_{oc} , of 0.600 volt. These properties relate to the silicon substrate, p-n junction, and silicon surface condition. The effect of metal covering (and thus shadowing) the front surface must still be included. Using the ideal diode equation, the generation current density and open circuit voltage may be used to calculate the diode saturation current density, J_{sat} . Thus,

$$J_{\text{out}} \cong J_{\text{gen}} - J_{\text{sat}} \exp[qV/kT]; \quad (1)$$

$$0 = J_{\text{gen}} - J_{\text{sat}} \exp[qV_{\text{oc}}/kT]; \quad (2)$$

$$J_{\text{sat}} = \frac{J_{\text{gen}}}{[\exp qV_{\text{oc}}/kT]} \quad (3)$$

From equation (3), the reference cell has a saturation current density of $3.48 \times 10^{-9} \text{mA}/\text{cm}^2$.

As stated earlier, power output and conversion efficiency will depend directly on solar cell size. Larger cell sizes generate greater currents and

require longer metal paths from the cell center to the perimeter. Longer current conduction paths require increased front surface metal coverage, or increased metal thickness, if series resistance is not to be increased. Increases in series resistance result directly in reduced cell efficiency. Therefore, the relation between cell surface area, series resistance, and power conversion efficiency must be evaluated. This is done by utilizing the ideal diode equation.

Let A be the total solar cell front surface area (in cm^2 , including metal coverage), and let R be the series resistance (in ohms). The equation describing the electrical behavior becomes

$$AJ_{\text{out}} \cong fAJ_{\text{gen}} - AJ_{\text{sat}} \exp \left(\frac{q}{KT} [V + RAJ_{\text{out}}] \right) \quad (4)$$

J_{out} and J_{sat} are calculated on the basis of total values and total surface area of the solar cell, so that

$$J_{\text{out}} = I_{\text{out}}/A \quad (5)$$

$$\text{and } J_{\text{sat}} = I_{\text{sat}}/A \quad (6)$$

J_{gen} is the photogenerated current per unit area of exposed surface, and F is the fraction of the cell surface that is not covered with metal (i.e., the fraction of cell surface is exposed).

Solving the above equations for voltage, V , yields

$$V = \frac{kT}{q} \ln \left[\frac{fJ_{\text{gen}} - J_{\text{out}}}{J_{\text{sat}}} \right] - RAJ_{\text{out}} \quad (7)$$

Power, P , is voltage times output current.

$$P = VAJ_{\text{out}} \quad (8)$$

$$P = \frac{kT}{q} A J_{\text{out}} \ln \left[\frac{fJ_{\text{gen}} - J_{\text{out}}}{J_{\text{sat}}} \right] - RA^2 J_{\text{out}}^2 \quad (9)$$

Differentiating,

$$\frac{dP}{dJ_{\text{out}}} = A \frac{kT}{q} \ln \left[\frac{fJ_{\text{gen}} - J_{\text{out}}}{J_{\text{sat}}} \right] \quad (\text{equation continued})$$

$$- A \frac{kT}{q} J_{out} \left[\frac{1}{J_{sat}} \right] \left[\frac{J_{sat}}{fJ_{gen} - J_{out}} \right] - 2 RA^2 J_{out} \quad (10)$$

By definition, at maximum output power the voltage $V=V_m$ and the current density $J_{out} = J_m$. To solve for J_m , set $dP/d J_{out} = 0$.

The resulting non-linear equation is

$$RA = \frac{1}{2} \frac{kT}{q} \frac{1}{J_m} \left\{ \ln \left[\frac{fJ_{gen} - J_m}{J_{sat}} \right] - \frac{J_m}{fJ_{gen} - J_m} \right\} \quad (11)$$

where RA is expressed in $K\Omega \text{ cm}^2$ when the current densities, J , are in mA/cm^2 .

From equations (7) and (11),

$$V_m = \frac{kT}{q} \ln \left[\frac{fJ_{gen} - J_m}{J_{sat}} \right] - RA J_m \quad (12)$$

$$V_m = \frac{1}{2} \frac{kT}{q} \left\{ \ln \left[\frac{fJ_{gen} - J_m}{J_{sat}} \right] + \frac{J_m}{fJ_{gen} - J_m} \right\} \quad (13)$$

A graphical solution to these equations can be obtained by determining values of RA and of V_m for various J_m values. By forming the product of V_m and J_m , the maximum power density P_{dm} (in mW/cm^2) is obtained. Since the solar input power density is assumed to be 100mW/cm^2 , the P_{dm} value is numerically equivalent to percentage cell efficiency, η . Values of P_{dm} (and/or η) are plotted against RA in Figure 1 as a function of $[100(1-f)]$, the percentage of the total front surface area covered by metal. Values used for J_{gen} and J_{sat} are those assumed for the reference cell discussed earlier. It can be observed that as the RA product increases, cell efficiency falls off rapidly, asymptotically approaching zero independent of metal coverage. As the RA product is reduced, cell efficiency saturates at a level dependent upon shadowing by the front surface metal. Note that at a reasonable value of 5%

FIGURE 1: EFFICIENCY OF IDEAL REFERENCE SOLAR CELL VERSUS RESISTANCE-AREA PRODUCT, SHOWN AS A FUNCTION OF FRONT SURFACE METAL SHADOWING.

metal coverage, the parameters assumed for the reference cell allow a maximum cell efficiency of 18.6%. The reference cell has been assumed to be a very good quality solar cell.

Discussion up to this point has been general, not specifying the actual geometry of the cell or its metallization pattern. To understand the manner in which cell size influences cell efficiency, a specific example will be considered. Both cell shape and metal pattern design must be specified, as well as the diffused layer sheet resistance. To keep things as fundamental as possible, the cell is assumed to be fabricated on an infinitely long rectangular ribbon (to avoid accounting for end effects) which can be increased in width from a minimum of 2cm to any desired value. (This infinitely long cell assumption is a convenience for calculations, and does not materially effect the resulting conclusions). The metal pattern is assumed to be a grid of parallel lines running across the width of the ribbon and wrapping around both sides to eliminate the need for additional metal busses on the top cell surface. As a result, external electrical contacts to both sides of the ribbon are made on the bottom surface where the grid lines wrap around. As long as such electrical contacts are constrained to be at the perimeter of the cell (rather than through holes or channels within the center of the cell area) this metal pattern should be representative of a near-optimum design. It should be noted at this time that external wraparound contacts at all edges would allow a lower series resistance for the front surface pattern than allowing these contacts only at two edges, accomodating a somewhat larger solar cell size with the same performance as a smaller cell with contacts at two edges. This effect is maximum for a square geometry; the effect decreases as the rectangular shape increasingly deviates from that of a square. For shapes with an aspect ratio of three or four with respect to edge lengths, the two-edge contact assumption is reasonably accurate for present discussions. (Round cells have sufficiently poor

module packing factors that they are not considered here.)

The analysis is simplified by considering a 2cm long slice from the center of the ribbon as shown in Figure 2. The infinitely long ribbon can be considered to be an infinite number of these two-centimeter-long segments connected in parallel. In the data to be presented, the width of the segment was varied from 2cm to greater than 250cm. Therefore, the starting reference point is a 2cm x 2cm cell. The p-n junction is assumed to have been formed such that the front surface layer sheet resistance is 40 ohms per square. The metal pattern is assumed to have eight grid lines in the 2cm segment and the metal itself is assumed to have a sheet resistance of 0.01 ohms per square, a reasonable value for low cost metals. (Other calculations are presented in which the number of grid lines and the resistivity of the metal are varied.)

The task is now to determine cell efficiency (output power density) versus cell size (in this example, versus the ribbon cell width) for various percentages of metal coverage, for different metal thicknesses, and for different densities of metal lines. This can be accomplished by computing the solar cell resistance as a function of the parameters above, forming the product of resistance and cell area and then using the curves of Figure 1 to determine efficiency or output power density.

For this purpose, solar cell resistance is calculated in a fashion identical to base spreading resistance calculations for transistors: resistance is equated to average voltage loss divided by total output current. Lateral conduction of current through the diffused surface region and conduction of current through the metal paths each contribute a component to the voltage loss. It is assumed that the resistance to current flow vertically through the silicon substrate is negligible. The total solar cell is divided into units as shown in Figure 3, each unit having a single metal stripe. Accounting for the distributed effect of current generation and collection, the resistance of a

FIGURE 2: SCHEMATIC OF BASIC REFERENCE CELL
SEGMENT CONSIDERED FOR COST-EFFECTIVE
CELL SIZE TRADEOFFS.

FIGURE 3: DIAGRAM OF "UNIT CELL" SECTION OF BASIC REFERENCE CELL, USED FOR SERIES RESISTANCE COMPUTATIONS.

single unit is

$$R_u = \frac{1}{3} \rho_m \frac{W/2}{M} + \frac{1}{12} \rho_s \frac{S}{W/2} \quad (14)$$

$$R_u = \frac{1}{6} \rho_m \frac{W}{M} + \frac{1}{6} \rho_s \frac{S}{W} , \quad (15)$$

where ρ_m is the sheet resistance of the metal and ρ_s is the surface sheet resistance of the silicon. If the number of the metal stripes in the 2cm length of the cell is N, then there are 2N unit cells in parallel and the total resistance is

$$R = \frac{R_u}{2N} \quad (16)$$

$$R = \frac{1}{12N} \left[\rho_m \frac{W}{M} + \rho_s \frac{S}{W} \right] \quad (17)$$

Forming the RA product yields

$$RA = [R] [2W] \quad (18)$$

$$RA = \frac{W}{6N} \left[\rho_m \frac{W}{M} + \rho_s \frac{S}{W} \right] \quad (19)$$

Equation (19) can now be used with the graphical solutions shown in Figure 1 to illustrate cell efficiency as a function of solar cell width for the particular model chosen and for variations of various front surface metal configurations. These new graphical solutions are shown in Figures 4, 5, and 6. Figure 4 shows the effect of varying metal line width such that front surface shadowing varies from 2.5% to 40% (using 8 lines per 2cm segment for all five cases shown.) Figure 5 shows the results of holding surface metal coverage at a constant 10% but varying the number of lines per 2cm segment from 4 to 8 to 16. Figure 6 exhibits the effect of doubling the metal line thickness (not width) such that sheet resistance is halved. In all cases, the curve shapes are identical, being saturated at a level of efficiency determined by metal shadowing until the ribbon width is increased by a factor of five or ten, then falling rapidly

FIGURE 4: SOLAR CELL EFFICIENCY VERSUS RIBBON SUBSTRATE WIDTH, AS A FUNCTION OF METAL LINE WIDTH (i.e., FRONT SURFACE SHADOWING)

FIGURE 5: SOLAR CELL EFFICIENCY VERSUS RIBBON SUBSTRATE WIDTH, AS A FUNCTION OF NUMBER OF METAL STRIPES.

FIGURE 6: SOLAR CELL EFFICIENCY VERSUS RIBBON SUBSTRATE WIDTH, AS A FUNCTION OF METAL SHEET RESISTANCE (i.e., METAL LAYER THICKNESS)

and asymptotically approaching zero efficiency for ribbon widths greater than one hundred times the original 2cm.

The curves presented for the examples of Figures 4, 5, and 6 may be used, then, to determine a maximum allowable ribbon width if solar cell efficiency is not to drop below some arbitrary level such as 15% or 10%. As a general summary, these data indicate that ribbon width greater than about 20cm will lead to excessive losses of cell efficiency.

3.2.2 COST EFFECTIVENESS CONSIDERATIONS

Of course, the primary interest is not in cell efficiency alone but rather in the cost effective trade-offs involved in making cell size (ribbon width) larger at the expense of cell efficiency. As previously described, the impetus to increase cell size is the assumption that large area cells may be fabricated and processed more inexpensively than an equivalent silicon area comprised of smaller area cells. The cost effectiveness of losing cell efficiency while increasing cell size and reducing processing costs can be visualized by extending the example analysis presented above with a few basic assumptions about cost.

Assume first that the silicon cost per unit area is constant, independent of ribbon width W . The validity of this assumption is questionable since it is anticipated that the cost of silicon ribbon or sheet as a function of ribbon width will pass through a minimum making one width cheaper than others. As ribbon and sheet technologies mature, however, the basic cost of silicon will be a dominant factor, so the curve of ribbon cost vs. width will pass through a broad minimum, and the validity of this assumption is easily sufficient for this discussion. In addition, the cost per unit area of materials expended during cell and module fabrication and materials incorporated into the cell and encapsulation is also assumed constant. This assumption is expected to be generally valid. Therefore, a cell material cost per unit area, C_M , is

defined equal to silicon cost plus cell fabrication materials cost plus encapsulation materials cost.

Next assume that the processing cost per unit cell length is constant, independent of W . That is, cells of different widths, W , can be processed with identical throughputs and expense. In practice, it may not be possible to process very wide ribbons as inexpensively per unit length as narrow and moderate width ones. At any rate, a cell processing cost per unit length, C_P , is defined to include all costs other than materials, i.e., labor, depreciation, etc., for fabricating, interconnecting, and encapsulating cells. The cell processing cost per unit area then becomes C_P/W . Hence, the larger the ribbon width processed, the lower the not processing cost per unit area.

The total encapsulated solar cell cost per unit area, C_T , is now given by

$$C_T = C_M + \frac{C_P}{W} , \quad (20)$$

the sum of materials and processing costs, where C_M and C_P are both constants. A relation between C_M and C_P can be determined by considering a baseline cell fabrication and encapsulation process. Let the 2cm wide ribbon detailed in the previous calculations serve as the baseline. Processing this material would be similar to fabricating 2cm x 2cm solar cells, and the costs of materials and processing for such cells are well known.

It is now necessary to assume some relation between the materials cost and the processing cost. Let k be defined as the ratio of materials cost per unit solar cell area to processing cost per unit area for the baseline $W=2$ cm case. The value of k will be varied; but as a discussion point, a reasonable value for reference might be $k=2$, for which materials cost is 2/3, and processing cost is 1/3, of the total cost per unit area. Forming the ratio,

$$k = \left. \frac{C_M}{C_P/W} \right|_{W=2} = \frac{2 C_M}{C_P} \quad (21)$$

Therefore,

$$C_P = \frac{2}{k} C_M \quad (22)$$

As cell width increases beyond the baseline width, the total cost per unit area will decrease below the baseline cost value. Substituting equation (22) into equation (20) gives

$$C_T = C_M + \frac{1}{W} \left[\frac{2}{k} C_M \right] \quad (23)$$

$$= C_M \left[1 + \frac{2}{kW} \right] \quad (24)$$

Equation (24) expresses the total cost per unit area as a function of cell width, W , and a given assumed value of k .

In considering cost tradeoffs, it is desirable to minimize the total cost per watt of power output. Thus, the total cost per unit area, C_T , should be divided by the output power density. An equivalent figure of merit is obtained by dividing C_T by cell efficiency η . Both C_T and η are functions of cell width W . From equation (24),

$$\frac{C_T(W)}{\eta(W)} = C_M \left[1 + \frac{2}{kW} \right] \frac{1}{\eta(W)} \quad (25)$$

Values for $\eta(W)$ may be obtained from the curves of Figures 4, 5, and 6.

The parameter $C_T(W)/\eta(W)$ can be expressed as a percentage of the constant C_M , the materials cost per unit area.

Equation (25) is plotted in Figure 7 for several values of k for the case of 10% metal coverage, 8 lines per 2cm ribbon segment length, $\rho_m = .01\Omega/\square$, and $\rho_s = 40\Omega/\square$. For the reasonable value of $k=2$, the minimum cost per watt occurs for a ribbon width between 8 and 10cm. Other k values give different minima. For the more extreme case $k=0.2$, where processing costs are five times greater than materials costs (for 2cm width), the most cost-effective width is about 17cm. Note, however, that this case implies a higher cost per watt and a lower solar cell efficiency (as seen in Figure 4).

FIGURE 7: TOTAL COST PER UNIT EFFICIENCY (WHICH IS SIMILAR TO DOLLARS PER WATT) VERSUS RIBBON SUBSTRATE WIDTH. THIS IS SHOWN AS A FUNCTION THE RATIO OF MATERIAL COSTS TO PROCESSING COSTS FOR THE BASELINE CASE OF 2cm WIDE RIBBON.

It must be noted that as processes are developed to maturity and automated, the materials costs will be an increasing proportion of the total cost; the value of k will increase as a function of time. As the value of k increases, the most cost effective cell size decreases, but the sensitivity to cell size decreases below some maximum size. It should be observed that the parametric curves in Figure 7 were referenced to a 2cm cell width for an infinitely long cell. If, in fact, the reference cell had been assumed to be 20cm wide, the curve labeled $k=1$ would instead be labeled $k=10$. This in no way changes the concept that, regardless of chosen size, when materials costs become predominant over processing costs, the lower curves of Figure 7 (those having the highest values of the parameter k) show the limiting cost effectiveness of actual sizes. It is the projection here, that the optimum solar cell size will be less than 10cm. The attendant conclusion is that efforts to grow sheet greater than this size should not be pursued.

3.3 SELECTION OF PROCESSES AND PROCESS SEQUENCES

A solar cell is manufactured by a number of process steps which form a process sequence. As has been emphasized throughout this contract, there are many interactions between the individual process steps which must be considered in forming a process sequence.

Five process sequences which have a high probability of meeting the long range LSSA Project goals are presented in Tables 3 through 7.

The first process sequence, Table 3, utilizes only diffusion processes for junction formations; a planar p-n junction is produced. In this process sequence, one side of the substrate is texture etched while the other side is protected by a resist during texturing and hence remains flat. The texture-etched surface is then protected with an undoped spin-on (spray-on) silicon dioxide layer to mask against a boron diffusion on the back surface. Following back surface diffusion, the front surface is patterned to form the planar p-n junction area, followed by a phosphorous diffusion to form that junction. All dielectrics on the cell are now stripped, followed by deposition of a silicon nitride layer to form the antireflection coating. At this point, two options exist. The first, and simpler, option is to pattern the cell front dielectric with the desired metallization pattern and strip the back surface dielectric. This is followed by a plated and solder coated metallization. The second option, if it is desired to obtain a deeper p-n junction under the contact metal, is to modify the sequence to add an additional phosphorus diffusion into the contact areas. While forming the front surface contact pattern, the back surface dielectric is protected, leaving it to serve as a diffusion mask. Following the contact enhancement diffusion, this back surface dielectric is stripped and the cell metallized.

The second process sequence, Table 4, combines diffusion and ion implantation steps to form junctions. A blanket p^+ boron diffusion is performed simultaneously

with the growth of an oxide layer. One side of the substrate is then protected while the other is stripped of oxide and texture etched. The substrate is then coated with a film of silicon nitride, which, among other functions, will ultimately act as the antireflection coating. The metallization pattern is formed by etching into the silicon nitride layer, simultaneously clearing the back surface. The substrate is then ion implanted to form the P-N junction, during which the edges of the substrate are mechanically masked so that the P-N junction will be planar. Implantation is performed such that peak dopant concentration occurs near the silicon-dielectric interface, enhancing the electric field configuration for improved carrier collection. Implantation into the contact areas is deeper and produces a higher concentration than in areas covered by silicon nitride, resulting in a deeper P-N junction depth beneath the metallization areas. After the next step of activation annealing, the cell is metallized by plating and soldering.

The third process sequence utilizes only ion implantation for junction formations, Table 5. As in the first sequence, the wafer is texture-etched on one side. Next, the silicon nitride antireflection coating is deposited, patterned on the front surface and stripped from the back surface. Two ion implantation steps follow: P^+ (boron) into the back surface and N^+ (phosphorus), again mechanically masked to form a planar junction, into the front surface. Both implants are simultaneously activated through an anneal, followed by metallization plating and solder coating.

The fourth process sequence, Table 6, is an all diffusion process sequence. A blanket P+ boron diffusion is performed on both sides of the silicon substrate, simultaneously growing a silicon dioxide layer. The wafer back is then protected, the front oxide removed, the resist removed, and the exposed silicon surface texture etched. A phosphorous diffusion is then performed into the textured front surface. Following this diffusion, the wafer is resisted, front and back, patterned on the front, and mesa etched on the substrate edge. The cell is then coated with an antireflection layer of silicon nitride, passivating the P-N junction. Next, the silicon nitride is etched in a photo-resist step to form the front metallization pattern, while removing all dielectrics from the back surface. The cell is then metallized by plating and solder coating. This process sequence is more closely related to traditional solar cell manufacturing techniques and will be studied as a comparison baseline for the other process sequences.

The fifth process sequence, Table 7, is an all ion implanted (I^2) process sequence which differs from the sequence presented in Table 5 primarily in the order of the process steps. This difference, however, modifies the steps themselves dramatically. The sequence starts with a resist application to one side of the silicon substrate, the texture etching of the other side, and the removal of the resist. Following substrate cleaning, the wafer is first boron implanted on the back surface and then phosphorus implanted on the front through a mechanical mask to form the planar P-N junction. These implants do not pass through a dielectric film and, thus, must be performed at much lower voltages than in the sequence presented in Table 5 in which implants are performed through a dielectric film. Following implantation, an activation anneal is performed; this is followed by deposition of the silicon

TABLE 3: All diffusion process sequence resulting in planar type P-N junction. Option (b) for increase P-N junction depth beneath metallization contacts.

1. Resist back, Texture front, strip resist
2. Spin-on oxide, front
3. P^+ (boron) diffusion (back)
4. Pattern front (protect back) to form planar pattern
5. Phosphorous diffusion to form planar P-N junction
6. Strip both surfaces, and AR coat (both surfaces) with dielectric (silicon nitride)
 - (a) 7. Pattern front, strip back
 8. Metal
 - (b) 7. Pattern front, protect back
 8. Phosphorous diffusion - contact area
 9. Strip back
 10. Metal

TABLE 4: Combined diffusion and ion implantation process sequence resulting in planar P-N junction.

1. P^+ (boron) diffusion, front and back, and oxide growth
2. Strip front and texture etch
3. AR coat - dielectric
4. Pattern front, strip back
5. P^+ front - phosphorous (planar)
6. Activation anneal
7. Metal

TABLE 5: All ion implanted process sequence
with planar P-N junction.

1. Resist back, texture etch front, strip resist and clean
2. AR coat - dielectric
3. Pattern front, strip back
4. I^2 back - boron
5. I^2 front - phosphorous (planar)
6. Activation anneal
7. Metal

TABLE 6 :
ALL DIFFUSION PROCESS INCORPORATING PASSIVATED
MESA-ETCHED P-N JUNCTION PERIMETER

1. P+ (boron) diffusion, front and back, and oxide growth.
2. Strip front and texture etch.
3. Phosphorus diffusion
4. Mesa Etch
5. AR coat-dielectric
6. Pattern front, strip back
7. Metal

TABLE 7

ALL ION IMPLANTATION PROCESS WITH PLANAR
JUNCTION. BARE SILICON SURFACE IMPLANTATION.

1. Resist back, texture etch front, strip resist and clean.
2. I^2 back - boron.
3. I^2 front - phosphorus (planar)
4. Activation Anneal
5. AR coat - dielectric
6. Pattern front, strip back.
7. Metal

nitride antireflection coating. The antireflection coating is then patterned during a photoresist step to form the front metal pattern and to clear dielectric from the back surface. The cell is then metallized and solder coated.

The five process sequences which have now been presented are comprised of many common process steps. In some cases, a process step may be performed by several different techniques. A summary of distinct process steps which are being analyzed during this study is shown in Table 8.

3.4 DEFINITION OF PRIMARY PROCESS VARIABLES

Each of the process steps in Table 8 can be utilized in a satisfactory process sequence. Accordingly, to facilitate choice of an optimized process sequence, it is necessary that process variables be defined for each step in order to specify the details and control limits for each. This study is centered around the primary process variables, which, like solar cell variables, are those variables which can be controlled by the operator before and during performance of a process, while diagnostic variables are those variables which are measured after completion of a process step to determine changes effected by the step. In some cases, these diagnostic variables will also be the same as solar cell variables.

In order to effectively study the interaction of process and cell variables, some process variables may be specified in a process step definition. For example, a phosphorus diffusion could be performed from a variety of sources, the type of source being considered a variable. This could lead to a nearly infinite study matrix. To maintain a manageable study, one phosphorus source, phosphine (PH_3), will be "defined" as part of the process step for a phosphorus diffusion. This will increase the effectiveness of

TABLE 8:
PROCESS STEPS AND OPTIONS FOR INCLUSION IN
PROCESS SEQUENCES BEING STUDIED

1. Patterning Operations
 - a. Photoresist Application
 1. Spin
 2. Spray
 - b. Photoresist Removal
 1. Wet Chemistry
 2. Plasma
 - c. Photoresist alignment, exposure, development
 1. Spray development
 2. Immersion development
 - d. Ion implantation shadow masking
2. Etching Operations
 - a. Dielectric etching
 1. Wet Chemistry
 2. Plasma
 - b. Silicon etching
 1. Wet Chemistry
 2. Plasma
 - c. Texture etching
3. Cleaning Operations
 - a. Wet Chemistry
 - b. Centrifuge rinsing and drying
 - c. Plasma
 - d. Scrubbing
4. Dielectric Deposition
 - a. Silicon nitride
 - b. Spin-on (Spray-on) Oxide
5. Doping Operations
 - a. Diffusion
 1. Boron
 2. Phosphorus
 3. Arsenic

TABLE 8: (continued)

- b. Ion Implantation
 - 1. Boron
 - 2. Phosphorus
 - 3. Arsenic
 - c. Annealing (activation)
6. Metallization
- a. Plating
 - b. Sintering
 - c. Solder Coating

this study by allowing more attention to variables of processing which can be controlled by the process operator. Similar situations may exist for other process steps, and choices will be made to limit the scope of the study. Of course, considerable judgment must be exercised in such choices to guarantee that the selected process is at least near optimal for performance of the particular function.

The following tables (9 through 24) define the primary process variables for the chosen process steps. Where variables are common, processes have been grouped together for ease of presentation.

TABLE 9:
PROCESS VARIABLES FOR PHOTORESIST
APPLICATION AND SPIN-ON OXIDE APPLICATION

OPERATIONAL VARIABLES

SPINNING

Spin speeds
Application Sequences

SPRAYING

Pressure
Nozzle Configuration
Table Speed
Application Sequences

{	Type of Resist or Spin-on Material.
{	Viscosity
{	Dispense time and amount
{	Preparation of Surface
{	Bake time, temperature, heat source, and ambient
{	Substrate surface quality and texture

DIAGNOSTIC VARIABLES

Coverage thickness
Coating uniformity
Adherence
Etch resistance
Index of refraction (oxide)

TABLE 10:

PROCESS VARIABLES FOR PHOTORESIST REMOVAL

OPERATIONAL VARIABLESPLASMA

Gas Composition

Gas Pressure

Gas Flow Rate

Gas Flow Pattern

RF Power and Frequency

Time

Chamber Size

Chamber Geometry

WET CHEMISTRY

Chemical Composition

Temperature

Time

Spacing

Agitation

Rinse Cycle(s)

Bath Size

DIAGNOSTIC VARIABLES

Visible Residue

Contamination, e.g., metallic ion residues

TABLE 11:
PROCESS VARIABLES FOR PHOTORESIST ALIGNMENT,
EXPOSURE, AND DEVELOPMENT

OPERATIONAL VARIABLES

Type of process (proximity, projection, contact)
Variations in substrate dimensions
Thickness of photoresist
Substrate positioning
Mask type
Light intensity and uniformity
Exposure time
Surface quality
Development Method:
 Spray -- pressure and nozzle configuration
 Immersion -- agitation

Development Time

Developer Temperature
Developer composition
Rinsing and drying cycles
Bake time, temperature, and ambient

DIAGNOSTIC VARIABLES

Pattern dimensions
Pattern location
Pattern integrity
Completeness of pattern development

TABLE 12:
PROCESS VARIABLES FOR ION IMPLANTATION SHADOW MASKING

OPERATIONAL VARIABLES

Variations in silicon dimensions
Mask and holder design and tolerances
Material of mask construction
(knock-on impurities)

DIAGNOSTIC VARIABLES

Pattern (junction edge) position

TABLE 13:
PROCESS VARIABLES FOR WET ETCHING AND CLEANING
OF DIELECTRICS AND SILICON

OPERATIONAL VARIABLES

Dielectric or silicon characteristics
(Thickness, doping, composition, etch rate, stain, etc.)
Bath composition and purity of chemicals
Bath temperature
Time of etching (and end point determination)
Agitation
Bath size, life, and loading factors
Substrate preparation
Substrate rinsing

DIAGNOSTIC VARIABLES

Adequate removal criteria
Pattern definition (if applicable)

TABLE 14:
PROCESS VARIABLES FOR PLASMA ETCHING AND CLEANING
OF DIELECTRICS AND SILICON

OPERATIONAL VARIABLES

Dielectric or silicon characteristics
(Thickness, doping, composition, etch rate,
stain, etch)
Gas composition and purity
Gas flow rates and pressure
Substrate spacing
RF power and frequency
Etch and cleaning cycle times
Chamber size
End point detection

DIAGNOSTIC VARIABLES

Adequate removal criteria
Pattern definition (if applicable)

TABLE 15:
PROCESS VARIABLES FOR TEXTURE ETCHING

OPERATIONAL VARIABLES

Bath composition
Bath temperature
Etching time
Purity of chemicals
Substrate starting surface
(mechanical condition and doping level)
Agitation
Bath size, life, and loading factors

DIAGNOSTIC VARIABLES

Completeness criteria
Quality and uniformity of texturing

TABLE 16:
PROCESS VARIABLES FOR CENTRIFUGE
RINSING AND DRYING

OPERATIONAL VARIABLES

Spin speed
Time
Temperature
Water pressure and purity
Gas pressure, purity, and type
Loading and balancing factors

DIAGNOSTIC VARIABLES

Completeness of drying
Filming or spotting by residues

TABLE 17:
PROCESS VARIABLES FOR HIGH PRESSURE SCRUBBING

OPERATIONAL VARIABLES

Pressure
Water purity
Nozzle configuration
Time
Dry spin-speed

DIAGNOSTIC VARIABLES

Cleanliness criteria

TABLE 18:
PROCESS VARIABLES FOR DIELECTRIC DEPOSITION
(e.g., LOW PRESSURE CHEMICAL VAPOR DEPOSITION OF SILICON NITRIDE)

OPERATIONAL VARIABLES

Reactor temperature and temperature profile
Reactor geometry
Substrate configuration in reactor
Sequence and time of cycles
RF energy (if used)
Gas compositions and purities
Pressure
Substrate surface preparation

DIAGNOSTIC VARIABLES

Film thickness
Film index of refraction
Uniformity:
 across substrate
 throughout reactor

TABLE 19:
PROCESS VARIABLES FOR DOPING BY DIFFUSION
(Selected source such as PH_3 , BCl_3)

OPERATIONAL VARIABLES

Furnace temperature and profile
Time, including portions of the cycle start and finish.
Gas mixture(s) and flow rates
Gas purities
Furnace tube size
Furnace cleanliness
Substrate spacing and orientation to gas flow
Insertion transients
Removal transients

DIAGNOSTIC VARIABLES

On a test wafer:
sheet resistivity
junction depth
oxide thickness and index of refraction
bulk lifetime
surface layer lifetime
Uniformity: across substrate, down furnace length

TABLE 20:
PROCESS VARIABLES FOR ION IMPLANTATION DOPING

OPERATIONAL VARIABLES

Dopant species
Voltage (or voltages)
Analysis quality
Beam currents and times: dose levels
Beam power density (heating); substrate temperature
Substrate surface quality
Substrate crystal orientation (channeling)
Dielectric surface layer species and thickness
Surface angle

DIAGNOSTIC VARIABLES

On a test wafer after activation annealing:
Sheet resistivity
Junction depth
Uniformity over a substrate
Uniformity substrate-to-substrate
Bulk lifetime
Surface layer lifetime

TABLE 21:

PROCESS VARIABLES FOR ACTIVATION ANNEALING

OPERATIONAL VARIABLES

Temperature
Time and heating rate
Dose, species, and energy of implant
Ambient gas(es) and flow rates
Substrate spacing

DIAGNOSTIC VARIABLES

Sheet resistivity
Junction depth
Uniformity over a substrate
Uniformity substrate-to-substrate
Bulk lifetime
Surface lifetime

TABLE 22:
PROCESS VARIABLES FOR PLATING

OPERATIONAL VARIABLES

Bath composition and purity of components
Bath temperature
Immersion time
Agitation
Substrate dopant type and level
Bath size, life, and loading factors
Substrate spacing
Substrate surface preparation
Substrate rinsing time and temperature
Drying process

DIAGNOSTIC VARIABLES

Metal thickness and uniformity
Metal series resistance
Metal-silicon contact resistance
Adhesion
Uniformity of subsequent solder coating

TABLE 23:

PROCESS VARIABLES FOR METALLIZATION SINTERING

OPERATIONAL VARIABLES

Temperature
Times of sequences for cycle
Ambient gas and gas flow rate
Substrate spacing

DIAGNOSTIC VARIABLES

Metal adherence
Metal penetration into silicon
Contact resistance
Effects on photovoltaic parameters
Color changes (if silicides or oxides form)
Uniformity of subsequent solder coating

TABLE 24:
PROCESS VARIABLES FOR SOLDER COATING

OPERATIONAL VARIABLES

Solder composition
Flux
Dross inhibitor
Temperature of solder
Time in solder
Method of substrate support
Contamination and bath life
Cleaning solution(s)

DIAGNOSTIC VARIABLES

Uniformity and thickness of solder coating
Series resistance of solar cell
Solar cell cleanliness

3.5 RELATIONSHIPS BETWEEN PRIMARY PROCESS VARIABLES AND CELL VARIABLES

The primary process variables listed in Tables 9 through 24 are related, in varying degrees, to the primary solar cell variables listed in Tables 1 and 2. In fact, it is recognized that nearly all of the cell variables and process variables are interrelated, so that changing any one will affect many others.

The direct and indirect relations between primary process variables and primary cell variables are presented, in a qualitative fashion, in Tables 25 through 41. Each of these tables is separated into two portions, A and B, with the "A" tables relating primary process variables (both operational and diagnostic) to primary solar cell operational variables and the "B" tables relating the same process variables to the solar cell diagnostic variables.

Since nearly all of the designated variables are interrelated, showing such relations on these tables would result in the tables being mostly filled, reducing their usefulness. Accordingly, entries on the tables are restricted to the several variables most strongly affected and those which would most readily and likely be evaluated for changes.

There are several judgements to be exercised in determining whether a relationship between a process variable and a solar cell variable is direct, indirect, or sufficiently remote that the interaction would be noted only after eliminating several other more direct interactions. The principal guideline for a direct relationship between a cell and process variable has been chosen to be that there is a strong, empirically observable link between changes in a process variable resulting in changes in solar cell characteristics.

For the sake of this analysis, it is assumed that the chosen process is, (It must be noted that, if the solar cell process were to be developed from

55

[illegible]

TABLE 25B: VARIABLES FOR PHOTORESIST APPLICATION		DIAGNOSTIC SOLAR CELL VARIABLES																					
		x_j	x_m	ρ_s	ρ_{sm}	ρ_s back	x_j back	ρ	C_s	C_s back	$C(x)$	$C(x)$ back	(hkl)	N_L	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	W_B	d	Uniformity	
56	<u>OPERATIONAL PROCESS VARIABLES</u>																						
	<u>SPINNING</u>																						
	Spin Speeds		(X)																				
	Application Sequences																						
	<u>SPRAYING</u>																						
	Pressure		(X)																				
	Nozzle Configuration		(X)																				
	Table Speed		(X)																				
	Application Sequences																						
	Type of Resist		(X) (X)																				
	Viscosity		(X)																				
	Dispense time and amount		(X) (X)																				
Bake time, temperature, heat source and ambient		X																					
Substrate surface quality and texture																							
<u>DIAGNOSTIC PROCESS VARIABLES</u>																							
Coverage thickness		X																					
Coating uniformity		*																					
Adherence																							
Etch resistance																							

TABLE 26A:
VARIABLES FOR MASKING SPIN-ON OXIDE APPLICATION

	OPERATIONAL SOLAR CELL VARIABLES																
	I_{sc}	V_{oc}	P_{max}	η	$V_{P_{max}}$	$I_{P_{max}}$	P_{max}	FF	R_{series}	R_{shunt}	t	D	L	W	A	A_j	A_M
<u>OPERATIONAL PROCESS VARIABLES</u>																	
<u>SPINNING</u>																	
Spin Speeds												X	X	X			
Application Sequences															(X)		
<u>SPRAYING</u>																	
Pressure																	
Nozzle Configuration												X	X	X			
Table Speed												X	X	X			
Application Sequences															(X)		
Viscosity															(X)		
Dispense time and amount																	
Preparation of surface																	
Bake time, temperature, heat source, and ambient																	
Substrate surface quality and texture																	
<u>DIAGNOSTIC PROCESS VARIABLES</u>																	
Coverage thickness																	
Coating uniformity																	
Adherence																	
Index of refraction																	

TABLE 26B:
VARIABLES FOR MASKING SPIN-ON OXIDE APPLICATION

DIAGNOSTIC SOLAR CELL VARIABLES

[illegible]

50

[illegible]

DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 27B:
VARIABLES FOR PHOTORESIST REMOVAL

OPERATIONAL PROCESS VARIABLES

PLASMA

Gas Composition
Gas Pressure
Gas Flow Rate
Gas Flow Pattern
RF Power and Frequency

Time

Spacing

Chamber Size

Chamber Geometry

WET CHEMISTRY

Chemical Composition

Temperature

Time

Spacing

Agitation

Rinse Cycle(s)

Bath Size

DIAGNOSTIC PROCESS VARIABLES

Visible Residue

Contamination, e.g., metallic ion
residues

	x_j	x_m	ρ_s	ρ_{sm}	$\rho_{s \text{ back}}$	$x_j \text{ back}$	ρ	C_s	$C_{s \text{ back}}$	$C(N)$	$C(x) \text{ back}$	(hkl)	N_L	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	W_B	W	Uniformity
Gas Composition												(X)		(X)		(X)					
Gas Pressure																					X
Gas Flow Rate																					X
Gas Flow Pattern																					X
RF Power and Frequency																					
Time																					
Spacing																					X
Chamber Size																					
Chamber Geometry																					
Chemical Composition												(X)		(X)		(X)					
Temperature																					
Time																					
Spacing																					X
Agitation																					X
Rinse Cycle(s)														(X)		(X)					
Bath Size																					
Visible Residue													X	(X)	(X)	(X)				X	
Contamination, e.g., metallic ion residues												(X)	X	(X)	X				X		

TABLE 28A:
VARIABLES FOR PHOTORESIST ALIGNMENT, EXPOSURE,
AND DEVELOPMENT

TABLE 28A: VARIABLES FOR PHOTORESIST ALIGNMENT, EXPOSURE, AND DEVELOPMENT		OPERATIONAL SOLAR CELL VARIABLES																				
		I_{sc}	V_{oc}	P_{max}	η	$V_{P_{max}}$	$I_{P_{max}}$	FF	R_{series}	R_{shunt}	t	D	L	N	A	A_j	A_M	$(A_M/A_j) \times 100\%$	C_M	W_M	L_M	
<u>OPERATIONAL PROCESS VARIABLES</u>																						
Type of process (proximity, projection, contact)																			(X)	(X)		
Variations in substrate dimensions															(X)	(X)						
Thickness of photoresist																						
Substrate positioning																						
Mask type																						
Light intensity and uniformity																						
Exposure time																						
9	Surface quality																					
Development Method:																						
Spray -- pressure and nozzle configuration																						
Immersion -- agitation																						
Development time																						
Developer temperature																						
Developer composition																						
Rinsing and drying cycles		(X)						(X)		(X)												
Bake time, temperature, and ambient		(X)						(X)		(X)												
<u>DIAGNOSTIC PROCESS VARIABLES</u>																						
Pattern dimensions											(X)	(X)	(X)		(X)	(X)	(X)		X	X		
Pattern location																						
Pattern integrity						(X)	(X)		(X)	(X)												
Completeness of pattern development		(X)	(X)					(X)	(X)	(X)					(X)	(X)						

[illegible]

FIGURE 29A:
VARIABLES FOR ION IMPLANTATION SHADOW MASKING

FIGURE 29A: VARIABLES FOR ION IMPLANTATION SHADOW MASKING		OPERATIONAL SOLAR CELL VARIABLES																			
		I_{sc}	V_{oc}	P_{max}	η	V_{pmax}	I_{pmax}	FF	R_{series}	R_{shunt}	t	D	L	W	A	A_j	A_M	$(A_M/A_j) \times 100\%$	t_M	W_M	L_M
<u>OPERATIONAL PROCESS VARIABLES</u>																					
Variations in silicon dimensions										*	*	*	*	*							
Mask and holder design and tolerances		X		(X)	(X)		(X)			X	X	X	X	X	X			(X)			
Material of Mask Construction (knock-on impurities)		X	X	(X)	(X)	(X)	(X)	X		X											
<u>DIAGNOSTIC PROCESS VARIABLES</u>																					
Pattern (Junction edge) position		X		(X)	(X)		(X)			(X)	X	X	X	X	X			(X)			

DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 29B:
VARIABLES FOR ION IMPLANTATION SHADOW MASKING

	x_j	x_m	ρ_s	ρ_{sm}	ρ_s back	x_j back	ρ	C_s	C_s back	$C(x)$	$C(x)$ back	(hkL)	N_L	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	W_B	β	Uniformity
<u>OPERATIONAL PROCESS VARIABLES</u>																					
Variations in silicon dimensions																					X
Mask and holder design and tolerances																(X)					
Material of Mask Construction (knock-on impurities)														X	X	X	(X)				
<u>DIAGNOSTIC PROCESS VARIABLES</u>																					
Pattern (Junction edge) position																(X)					

TABLE 30A:
VARIABLES FOR WET ETCHING AND CLEANING OF
DIELECTRICS AND SILICON

OPERATIONAL SOLAR CELL VARIABLES

OPERATIONAL PROCESS VARIABLES

Dielectric or Silicon Characteristics
(Thickness, doping, composition,
etch rate, strain, etc.)

Bath composition and purity of chemicals

Bath temperature

Time of etching (and end point
determination)

Agitation

Bath size, life, and loading factors

Substrate preparation

Substrate rinsing

DIAGNOSTIC PROCESS VARIABLES

Adequate removal criteria

Pattern definition (if applicable)

	I_{sc}	V_{oc}	P_{max}	η	V_p	P_{max}	I_p	FF	R series	R shunt	t	D	L	W	A	A_j	A_M	$(A_M/A_j) \times 100\%$	t_M	W_M	I_M
Dielectric or Silicon Characteristics (Thickness, doping, composition, etch rate, strain, etc.)	X	X	(X)	(X)	(X)	(X)	X										(X)	(X)	(X)	X	X
Bath composition and purity of chemicals	(X)	(X)						(X)	(X)	(X)											
Bath temperature	(X)	(X)																			
Time of etching (and end point determination)	(X)	(X)														(X)	(X)				
Agitation	(X)	(X)									X	X	X	(X)	(X)	(X)	(X)				
Bath size, life, and loading factors	(X)	(X)									(X)	(X)	(X)	X	X	X					
Substrate preparation								(X)	(X)	(X)											
Substrate rinsing																					
Adequate removal criteria	(X)	(X)						(X)	(X)	(X)											
Pattern definition (if applicable)																	(X)	(X)	(X)	X	X

TABLE 30B:
VARIABLES FOR WET ETCHING AND CLEANING OF
DIELECTRICS AND SILICON

DIAGNOSTIC SOLAR CELL VARIABLES

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TABLE 30B:
VARIABLES FOR WET ETCHING AND CLEANING OF
DIELECTRICS AND SILICON

	x_j	x_m	ρ_s	ρ_{sm}	ρ_s back	x_j back	ρ	C_s	C_s back	$C(x)$	$C(x)$ back	(hkL)	N_L	$I_{SC}(A)$	τ	$I_{vs V}$	S	$R(A)$	W_B	H	Uniformity
<u>OPERATIONAL PROCESS VARIABLES</u>																					
Dielectric or Silicon characteristics (Thickness, doping, composition, etch rate, strain, etc.)														X		X	(X)	X			X
Bath composition and purity of chemicals															(X)	(X)	(X)	(X)			
Bath temperature																		(X)			
Time of etching (and end point determination)																		(X)			(X)
Agitation																		(X)			X
Bath size, life, and loading factors																					(X)
Substrate preparation																					X
Substrate rinsing																					
<u>DIAGNOSTIC PROCESS VARIABLES</u>																					
Adequate removal criteria																					
Pattern definition (if applicable)																					(X)

TABLE 31A:
VARIABLES FOR PLASMA ETCHING AND CLEANING OF
DIELECTRICS AND SILICON

TABLE 31A: VARIABLES FOR PLASMA ETCHING AND CLEANING OF DIELECTRICS AND SILICON		OPERATIONAL SOLAR CELL VARIABLES																				
		I_{sc}	V_{oc}	P_{max}	η	V_p	P_{pmax}	I_{pmax}	FF	R_{series}	R_{shunt}	ϵ	D	L	W	A	A_j	A_M	$(A_M/A_j) \times 100\%$	ϵ_M	η_M	L_M
<u>OPERATIONAL PROCESS VARIABLES</u>																						
Dielectric or Silicon Characteristics (Thickness, doping, composition, etch rate, strain, etc.)		X	X	(X)	(X)	(X)	(X)	X									(X)	(X)	(X)	X	X	
Gas composition and purity		(X)	X					X	X	X												
Gas flow rates and pressure		(X)	(X)																			
Substrate spacing		(X)	(X)								(X)	X	X	X	X							
RF power and frequency		(X)	(X)												(X)	X	X					
Etch and cleaning cycle times		(X)	(X)									(X)	(X)	(X)	(X)	X	X					
Chamber size		(X)	(X)									X	X	X	(X)							
End point detection		(X)	(X)													(X)	(X)					
<u>DIAGNOSTIC PROCESS VARIABLES</u>																						
Adequate removal criteria		(X)	(X)					(X)	(X)	(X)												
Pattern definition (if applicable)																	(X)	(X)	(X)	X	X	

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[illegible]

Dielectric or Silicon Characteristics
(Thickness, doping, composition,
etch rate, strain, etc.)

Gas flow rates and pressure

Substrate spacing

RF power and frequency

Etch and cleaning cycle times

Chamber size

End point detection

Adequate removal criteria

Pattern definition (if applicable)

TABLE 32A:
VARIABLES FOR TEXTURE ETCHING

OPERATIONAL SOLAR CELL VARIABLES

OPERATIONAL PROCESS VARIABLES

Bath composition

(X)

Bath temperature

(X)

Etching time

(X)

Purity of chemicals

(X)

(X)

Substrate starting surface
(mechanical condition and doping
level)

X

X

X

(X)

Agitation

X

X

X

X

Bath size, life, and loading factors

DIAGNOSTIC PROCESS VARIABLES

Completeness criteria

X

(X)

Quality and uniformity of texturing

(X)

(X)

DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 32B:
VARIABLES FOR TEXTURE ETCHING

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<u>OPERATIONAL PROCESS VARIABLES</u>																				
Bath composition												(X)		(X)	X					
Bath temperature												(X)			(X)					
Etching time												(X)			(X)					
Purity of chemicals													(X)		(X)					
Substrate starting surface (mechanical condition and doping level)										X	(X)								X	(X)
Agitation																				
Bath size, life, and loading factors																				
<u>DIAGNOSTIC PROCESS VARIABLES</u>																				
Completeness criteria										X					X				X	
Quality and uniformity of texturing										X					(X)				X	

TABLE 33A:
VARIABLES FOR CENTRIFUGE RINSING AND DRYING

TABLE 33A: VARIABLES FOR CENTRIFUGE RINSING AND DRYING		OPERATIONAL SOLAR CELL VARIABLES																				
		I_{sc}	V_{oc}	P_{max}	η	$V_{P_{max}}$	$I_{P_{max}}$	FF	R_{series}	R_{shunt}	t	D	L	W	A	A_j	A_M	$(A_M/A_j) \times 100\%$	t_M	W_M	L_M	
<u>OPERATIONAL PROCESS VARIABLES</u>																						
Spin speed																						
Time																						
Temperature																						
Water pressure and purity								(X)	(X)													
Gas pressure, purity, and type										X	X	X	X	(X)								
Loading and balancing factors																						
<u>DIAGNOSTIC PROCESS VARIABLES</u>																						
Completeness of drying																						
Filming or spotting by residues		(X)						(X)	(X)													
Breakage of substrates										X	(X)	(X)	(X)									

TABLE 33B:
VARIABLES FOR CENTRIFUGE RINSING AND DEYING

DIAGNOSTIC SOLAR CELL VARIABLES

[illegible]

TABLE 34A:
VARIABLES FOR HIGH PRESSURE SCRUBBING

[illegible]

TABLE 34B:
VARIABLES FOR HIGH PRESSURE SCRUBBING

DIAGNOSTIC SCALAR CELL VARIABLES

OPERATIONAL PROCESS VARIABLES

Pressure

Water purity

Nozzle configuration

Time

Dry spin-speed

DIAGNOSTIC PROCESS VARIABLES

Cleanliness criteria

x_i	λ_m	ρ_s	ρ_{sm}	ρ_s back	x_i back	ρ	C_s	C_s back	$C(x)$	$C(x)$ back	(hkl)	N_L	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	W_b	d	Uniformity
														(X)		(X)				
														(X)		(X)				(X)
																				(X)
														(X)	(X)	(X)				(X)

TABLE 35A:
VARIABLES FOR DIELECTRIC DEPOSITION
(e.g., LOW PRESSURE CHEMICAL VAPOR DEPOSITION
OF SILICON NITRIDE)

OPERATIONAL SOLAR CELL VARIABLES																						
I_{sc}	V_{oc}	P_{max}	η	V_p	P_{max}	I_{pmax}	FF	R_{series}	R_{shunt}	ϵ	D	L	W	A	A_j	A_M	$(A_M/A_j) \times 100\%$	ϵ_M	η_M	L_M		
(X)	(X)										(X)	(X)	(X)	(X)								
							(X)		(X)													
(X)																						
X	(X)					(X)																
X	(X)					(X)																
(X)											(X)	(X)	(X)	(X)								
(X)																						

DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 35B:
VARIABLES FOR DIELECTRIC DEPOSITION
(e.g., LOW PRESSURE CHEMICAL VAPOR DEPOSITION
OF SILICON NITRIDE)

OPERATIONAL PROCESS VARIABLES

Reactor temperature and temperature
profile
Reactor geometry
Substrate configuration in reactor
Sequence and time of cycles
RF energy (if used)
Gas compositions and purities
Pressure
Substrate surface preparation

DIAGNOSTIC PROCESS VARIABLES

Film thickness
Film index of refraction
Uniformity:
 across substrate
 throughout reactor

	x_i	x_m	ρ_s	ρ_{sm}	$\rho_{s \text{ back}}$	$x_j \text{ back}$	ρ	C_s	$C_{s \text{ back}}$	$C(x)$	$C(x) \text{ back}$	(hkl)	N_L	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	W_b	$\bar{M}$	Uniformity
(X)						(X)		(X)	(X)	(X)	(X)					(X)					(X)
																					(X)
																					(X)
															X		X				
																					(X)
																					(X)
														X				X			
														X				X			
																					*
																					*

TABLE 36A:
VARIABLES FOR DOPING BY DIFFUSION
(Selected source such as PH_3 , BCl_3)

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DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 36B:
VARIABLES FOR DOPING BY DIFFUSION
(Selected source such as PH_3 , BCl_3)

OPERATIONAL PROCESS VARIABLES

	x_j	x_m	ρ_s	ρ_{sm}	ρ_s back	x_j back	ρ	C_s	C_s back	$C(x)$	$C(x)$ back	(hkl)	N_L	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	E_B	H	Uniformity
Furnace temperature and profile	(X)	(X)		(X)	(X)		X	X	X	X		(X)			(X)						(X)
Time, including portions of the cycle start and finish	(X)	(X)		(X)	(X)		X	X	X	X		(X)			(X)						(X)
Gas mixture(s) and flow rates	(X)	(X)		(X)	(X)										(X)						X
Gas purities														(X)	X	(X)	X				
Furnace tube size																					X
Furnace cleanliness												(X)	(X)	X	(X)	X					(X)
Substrate spacing and orientation to gas flow																					X
Insertion transients												(X)		(X)		(X)					(X)
Removal transients												(X)		(X)		(X)					(X)

DIAGNOSTIC PROCESS VARIABLES

On a test wafer:

sheet resistivity	(X)	*		*	(X)		(X)	(X)	(X)	(X)				(X)	(X)	(X)					
junction depth	*	(X)		(X)	*		(X)	(X)	(X)	(X)			X		(X)			(X)			
oxide thickness and index of refraction							(X)	(X)								(X)					X
bulk lifetime						X							X	*	X						
surface layer lifetime		X		X			(X)	(X)	(X)	(X)			X	X		X					
Uniformity: across substrate, down furnace length																					*

TABLE 37A:
VARIABLES FOR ION IMPLANTATION DOPING

OPERATIONAL PROCESS VARIABLES

Dopant Species
Voltage (or Voltages)
Analysis quality
Beam currents and times: dose levels
Beam power density (heating); substrate temperature
Substrate surface quality
Substrate crystal orientation (channeling)
Dielectric surface layer species and thickness
Surface angle

DIAGNOSTIC PROCESS VARIABLES

On a test wafer after activation annealing:

Sheet resistivity
Junction depth
Uniformity over a substrate
Uniformity substrate-to-substrate
Bulk lifetime
Surface layer lifetime

OPERATIONAL SOLAR CELL VARIABLES

I_{sc}	V_{oc}	P_{max}	n	V_{pmax}	I_{pmax}	FF	R_{series}	R_{shunt}	t	D	L	A_j	A_M	$(A_M/A_j) \times 100\%$	ϵ_M	W_M	L_M
(X)	(X)					(X)											
(X)	(X)					(X)											
(X)						(X)	(X)										
(X)	(X)					(X)											
							(X)	(X)	(X)								
(X)	(X)					(X)		(X)									
(X)	(X)																
(X)	(X)																
(X)	X	(X)	(X)	(X)	(X)	(X)	X										
X	(X)	(X)	(X)	(X)	(X)	(X)		(X)									
	(X)					(X)											
X	X	(X)	(X)	(X)	(X)	(X)											
X	(X)	(X)	(X)	(X)	(X)	(X)	(X)										

DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 37A:
VARIABLES FOR ION IMPLANTATION DOPING

OPERATIONAL PROCESS VARIABLES

	x_j	x_{ni}	ρ_s	ρ_{sm}	$\rho_{s \text{ back}}$	$x_j \text{ back}$	ρ	C_s	$C_{s \text{ back}}$	$C(x)$	$C(x) \text{ back}$	$(h\nu/L)$	N_L	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	W_B	η	Uniformity
Dopant Species	X					X				(X)	(X)				(X)	(X)	(X)				
Voltage (or Voltages)	X					X		X	X	X	X		X	(X)			(X)				
Analysis quality															X		X				
Beam currents and times: dose levels	X		X		X	X		X	X	(X)	(X)		X	(X)		X	(X)				
Beam power density (heating); substrate temperature										(X)	(X)						(X)				(X)
Substrate surface quality	(X)					(X)		(X)	(X)												X
Substrate crystal orientation (channeling)	(X)					(X)		(X)	(X)			X									(X)
Dielectric surface layer species and thickness)	X					X		(X)	(X)												X
Surface angle	(X)					(X)		(X)	(X)												(X)

DIAGNOSTIC PROCESS VARIABLES

On a test wafer after activation
annealing:

Sheet resistivity	(X)		*		*	(X)		(X)	(X)	(X)	(X)				(X)	(X)	(X)				
Junction depth	*		(X)		(X)	*		(X)	(X)	(X)	(X)			X		(X)				(X)	
Uniformity over a substrate																					*
Uniformity substrate-to-substrate																					*
Bulk lifetime							X							X	*	X					
Surface layer lifetime			X		X			(X)	(X)	(X)	(X)			X	X		X				

TABLE 38A:
VARIABLES FOR ACTIVATION ANNEALING

OPERATIONAL PROCESS VARIABLES

Temperature
Time and heating rate
Dose, species, and energy of implant
Ambient gas(es) and flow rates
Substrate spacing

DIAGNOSTIC PROCESS VARIABLES

Sheet resistivity
Junction depth
Uniformity over a substrate
Uniformity substrate-to-substrate
Bulk lifetime
Surface lifetime

OPERATIONAL SOLAR CELL VARIABLES

I_{sc}	V_{oc}	P_{max}	η	V_p	P_{max}	I_p	P_{max}	FF	R_{series}	R_{shunt}	t	D	L	W	A	A_j	A_M	$(A_H/A_j) \times 100\%$	t_M	W_M	L_M
(X)	(X)							(X)				X	X	X	X						
(X)	(X)											X	X	X	X						
X	X	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)												
(X)	(X)							(X)				(X)	(X)	(X)	(X)						
											(X)	X	X	X	(X)	(X)					
(X)	X	(X)	(X)	(X)	(X)	(X)	(X)	X													
X	(X)	(X)	(X)	(X)	(X)	(X)	(X)		(X)												
	(X)							(X)													
X	X	(X)	(X)	(X)	(X)	(X)	(X)														
X	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)												

DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 38B:
VARIABLES FOR ACTIVATION ANNEALING

OPERATIONAL PROCESS VARIABLES

Temperature

Time and heating rate

Dose, species, and energy of implant

Ambient gas(es) and flow rates

Substrate spacing

DIAGNOSTIC PROCESS VARIABLES

Sheet resistivity

Junction depth,

Uniformity over a substrate

Uniformity substrate-to-substrate

Bulk lifetime

Surface lifetime

	x_j	x_m	ρ_s	ρ_{sm}	$\rho_{s \text{ back}}$	$x_j \text{ back}$	ρ	C_s	$C_{s \text{ back}}$	$C(x)$	$C(x \text{ back})$	$(hkL)/N_L$	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	w_B	δI	Uniformity
(X)		(X)		(X)	(X)		X	X	X	X		X		X	(X)	X				
(X)		(X)		(X)	(X)		X	X	X	X		X		(X)	(X)	(X)				
X		X		X	X		X	X	(X)	(X)		X	(X)		X	(X)				
(X)		(X)		(X)	(X)							(X)								X
																				X
(X)		*		*	(X)		(X)	(X)	(X)	(X)				(X)	(X)	(X)				
*		(X)		(X)	*		(X)	(X)	(X)	(X)			X		(X)		(X)			
																				*
							X													*
													X	*	X					
		X		X				(X)	(X)	(X)	(X)		X	X		X				

TABLE 39A:
VARIABLES FOR PLATING

	OPERATIONAL SOLAR CELL VARIABLES																
	I_{sc}	V_{oc}	P_{max}	η	V_{pmax}	I_{pmax}	FF	R_{series}	R_{shunt}	t	D	L	W	A	A_j	A_M	$(A_M/A_j) \times 100\%$
<u>OPERATIONAL PROCESS VARIABLES</u>																	
Bath composition and purity of components	(X)	(X)					(X)	(X)									(X)
Bath temperature								(X)									X
Immersion time								(X)									X
Agitation																	(X)
Substrate dopant type and level																	(X)
Bath size, life, and loading factors										X	X	X	(X)		X	(X)	X (X) (X)
Substrate spacing																	X
Substrate surface preparation								(X)									
Substrate rinsing time and temperature	(X)	(X)					(X)		(X)								
Drying process	(X)																
<u>DIAGNOSTIC PROCESS VARIABLES</u>																	
Metal thickness and uniformity								X									X
Metal series resistance			(X)					X									X X X
Metal-silicon contact resistance			(X)					X							X		(X) (X)
Adhesion			(X)	(X)	(X)		X	(X)	(X)						(X)		(X) (X) (X)
Uniformity of subsequent solder coating			(X)					X									(X) (X)

DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 39B:
VARIABLES FOR PLATING

OPERATIONAL PROCESS VARIABLES

Bath composition and purity of components

Bath temperature

Immersion time

Agitation

Substrate dopant type and level

Bath size, life, and loading factors

Substrate spacing

Substrate surface preparation

Substrate rinsing time and temperature

Drying process

DIAGNOSTIC PROCESS VARIABLES

Metal thickness and uniformity

Metal series resistance

Metal-silicon contact resistance

Adhesion

Uniformity of subsequent solder coating

	x_j	x_m	ρ_s	ρ_{sm}	$\rho_{s \text{ back}}$	$x_j \text{ back}$	ρ	C_s	$C_{s \text{ back}}$	$C_{(y)}$	$C_{(x) \text{ back}}$	(hkt)	N_L	$I_{SC}(\lambda)$	τ	$I_{vs V}$	S	$R(\lambda)$	W_B	M	Uniformity
				X											X	(X)	X	(X)		X	
				(X)				X	X							(X)					
				X				X	X							(X)					
		(X)		(X)				(X)	(X)												X
				(X)				X	X											(X)	X
																					X
																					X
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																					X
																					X
																					X

TABLE 40A:
VARIABLES FOR METALLIZATION SINTERING

[illegible]

DIAGNOSTIC SOLAR CELL VARIABLES

TABLE 40B:
VARIABLES FOR METALLIZATION SINTERINGOPERATIONAL PROCESS VARIABLES

	x_j	x_m	ρ_s	ρ_{sm}	ρ_s back	x_j back	ρ	C_s	C_s back	$C(x)$	$C(x)$ back	(hkl)	N_L	$I_{SC}(A)$	τ	$I_{vs V}$	S	$R(A)$	W_B	n	Uniformity
Temperature	(X)	X	(X)	X	(X)	(X)		(X)	(X)	(X)	(X)		(X)	(X)	X	X	X			X	(X)
Times of sequences for cycle	(X)	X	(X)	X	(X)	(X)		(X)	(X)	(X)	(X)		(X)	(X)	(X)	X	(X)			X	
Ambient gas and gas flow rate		(X)		(X)									(X)		(X)	(X)	(X)			(X)	X
Substrate spacing																				(X)	X

DIAGNOSTIC PROCESS VARIABLES

Metal adherence		X						(X)	(X)											*	(X)
Metal penetration into silicon		*		(X)									X		X	X	(X)			X	X
Contact resistance		X						X	X	(X)	(X)	(X)				X				X	X
Effects on photovoltaic parameters	(X)	X	(X)	X	(X)	(X)		(X)	(X)	(X)	(X)		X		X	X	(X)			X	X
Color changes (if silicides or oxides form)		X																			
Uniformity of subsequent solder coating			(X)																	(X)	X

TABLE 41A:
VARIABLES FOR SOLDER COATING

TABLE 41A: VARIABLES FOR SOLDER COATING		OPERATIONAL SOLAR CELL VARIABLES																			
		I_{sc}	V_{oc}	P_{max}	η	$V_{P_{max}}$	$I_{P_{max}}$	FF	R_{series}	R_{shunt}	t	D	L	W	A	A_J	A_M	$(A_M/A_J) \times 100\%$	t_M	W_M	L_M
<u>OPERATIONAL PROCESS VARIABLES</u>																					
Solder composition								(X)										(X)	(X)	(X)	
Flux								(X)										X	X	X	
Dross inhibitor								(X)										X			
Temperature of solder							(X)		(X)									(X)			
Time in solder							(X)		(X)												
Method of substrate support										X	X	X	X	(X)				X	X	X	
Contamination and bath life				(X)	(X)	(X)	(X)	(X)	X	X						X		X	X	X	
Cleaning solution(s)		(X)						(X)													
<u>DIAGNOSTIC PROCESS VARIABLES</u>																					
Uniformity and thickness of solder coating				(X)	(X)	(X)		(X)	X									X	X	X	
Series resistance of solar cell				(X)	(X)	(X)		(X)	*	(X)				(X)	X			X	X	X	
Solar cell cleanliness		(X)	(X)							(X)											

TABLE 41B:
VARIABLES FOR SOLDER COATING

DIAGNOSTIC SOLAR CELL VARIABLES

OPERATIONAL PROCESS VARIABLES

Solder composition

Flux

Dross inhibitor

Temperature of solder

Time in solder

Method of substrate support

Contamination and bath life

Cleaning solution(s)

DIAGNOSTIC PROCESS VARIABLES

Uniformity and thickness of solder coating

Series resistance of solar cell

Solar cell cleanliness

	x_j	x_m	ρ_s	ρ_{sm}	ρ_s back	x_j back	ρ	C_s	C_s back	$C(x)$	$C(x)$ back	(hkl)	N_L	$I_{SC}(\lambda)$	τ	I vs V	S	$R(\lambda)$	w_B	M	Uniformity
				X															X	X	
				(X)														(X)	X	X	
				(X)														(X)	X	X	
	(X)														(X)				(X)	X	
	(X)														(X)				(X)	X	
				X															X	X	
																	(X)				
	X		X												X						
	(X)		X												X					X	
														(X)	(X)		(X)			(X)	

scratch, the tables would contain many, many more relations. To do so, however, would be to ignore today's state-of-the-art.) The tables, then, form a diagnostic tool to allow observation of the effects of changing the values of the variables. It is intended that this is interactive from both the cell and the process parameters. For example, it may be utilized as a guide for trouble shooting when the cell parameters change adversely. On the other hand, it can be utilized to identify which processes and process variables should be studied for improving cell performance above some previous standard.

A further observation must be presented. Frequently, there are direct relations between operational process variables and diagnostic process variables which give only an indirect relation to some cell variables. For example, the spin-speed during a photoresist application has a direct relation to the photoresist thickness, but only an indirect relation to the linewidth of a pattern etched after exposing and developing that photoresist. Similarly, a change in a cell variable (as a result of a process variable) can result in direct effects on other cell variables, but generally will have only indirect effects on process variables.

For each of these tables, the following key is used:

- X Strong or direct relationship
- (X) Weak or indirect relationship
- * Primary process variable and solar cell variable are the same, by definition.

The definition of the terms for the solar cell variables is listed in Tables 1 and 2.

3.6 SELECTION OF EVALUATION TECHNIQUES

It has been determined that evaluation of process variables to establish control limits is best performed empirically in some cases and analytically in others. For example, the effects of ion implantation direction with respect to crystal orientation of the substrate are best determined experimentally. On the other hand, the effects on junction depth of changing a diffusion temperature a small amount are best determined by analytical techniques utilizing extensive data from the literature. In many cases, both experimental and analytical data are utilized to complement one another.

4.0 CONCLUSIONS

A solar cell model has been described, and solar cell variables defined as operational and/or diagnostic. These variables have been identified and listed. Solar cell dimensions (size) have been identified as primary solar cell variables having the greatest impact on performance, and yet a quantitative analysis of this interrelationship has never been undertaken. Accordingly, a quantitative technical and economic analysis has been presented to identify the maximum cost effective size of a solar cell. This analysis indicated that the optimum narrow dimension of a solar cell will be near (or smaller than) 10 cm.

Five process sequences have been identified as potentially satisfying the long range ERDA goals. A list of process steps, combining the steps of the five process sequences, is presented. The primary process operational and diagnostic variables for each process step are then identified.

The primary process variables are related, in a matrix, to the primary solar cell variables. The interrelations between variables are broad and complex, demanding control of many far-reaching effects to ensure overall successful process sequence operation.

5.0 RECOMMENDATIONS

No specific recommendations are given this month.

6.0 CURRENT PROBLEMS

No unresolved problems have occurred to date of this report.

7.0 WORK PLAN STATUS

The work plan is on schedule, as revised.

8.0 LIST OF ACTION ITEMS

No items requiring unusual action have come to light during this report period.

9.0 MILESTONES

Status of the program is shown on the Milestone Prediction and Accomplishment Chart Figure 1.

FIGURE 8
MILESTONE ACCOMPLISHMENT AND PREDICTION CHART

PREDICTED

ACCOMPLISHED

	A	M	J	J	A	S	O	N	D	J
Financial Management and Cost Reports	▲	▲	▲	▲	▲	▲	△	△	△	△
Monthly Technical Progress Reports		▲	▲		▲			△		
Quarterly Report						▲	△			
Annual Report	▲									
Final Report										△
Progress Meetings		▲					▲			
Task Integration Meetings					▲				△	

FIGURE 8 (Continued).

MILESTONE PREDICTION CHART
REPORTS AND DOCUMENTATION

△ SCHEDULE

▲ DELIVERED