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PHOTOVOLTAIC MECHANISMS IN POLYCRYSTALLINE THIN FILM
SILICON SOLAR CELLS

Eighth Month Technical Summary Report, July 31, 1979—March 31, 1980

By

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July 11, 1980

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Westinghouse R&D Center
Pittsburgh, Pennsylvania

and

The Pennsylvania State University
University Park, Pennsylvania

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1. SUMMARY

In the current program substantial progress has been made in two task areas: in modeling at the Pennsylvania State University and in grain boundary characterization at Westinghouse. The measurement technique development task is presently limited by delivery of components necessary to make a basic spot scanner. At the end of the present program we expect to have established a sound foundation for modeling, characterizing and understanding simple solar cells in good quality polycrystalline material.

The modeling effort at Penn State has resulted in a Bessel-Fourier series solution for carrier transport in right cylindrical grains. Minority carrier lifetime values and surface or grain boundary recombination velocity values can be set to model a wide range of physically important conditions. Several important results of the modeling effort have been obtained. First, diode opposing current, which determines open circuit voltage under given illumination conditions, can be rigorously treated by using an effective lifetime which depends on grain boundary recombination velocity and on grain geometry. Second, the current collection factor which determines short circuit current requires a more complex treatment than simple substitution of an effective lifetime value for the normal mid-grain minority carrier lifetime.

Based on earlier work at Westinghouse with laser-scanned Czochralski (CZ) polycrystalline silicon, we planned to use laser scanned photo response to assess effects of material treatments or cell processing on grain boundary (g.b.) electrical activity. Furthermore, we expected to correlate those results with details of photovoltaic performance of small diagnostic cells. Such cells would yield statistical information and reveal position dependent effects.

The relatively low photocurrent suppression at grain boundaries ($\leq 15\%$ maximum vs. $\sim 40\%$ maximum for CZ polysilicon with comparable excitation) in the Wacker SILSO we have obtained has complicated execution of this approach. In addition, the large grains in SILSO reduce the influence of grain boundaries on cell performance. With small diagnostic cells, the ratio of grain boundary length to cell area can vary widely.

Several attempts have been made to overcome these drawbacks, since the availability and generally good uniformity of Wacker SILSO make it an attractive material for baseline studies. We have tried to exploit the fact that wafers of SILSO can be correlated, that is identified as being taken in sequence from the original ingot. Sequential slice identification is possible in this material since the central portion of the ingot contains long columnar grains. Such correlated wafers have grain structure which is similar in geometric detail. With correlated material, studies have been made of effects of various surface preparation conditions (particularly different etchants) and their effects on detailed photovoltaic behavior. For these studies, all samples were prepared with MIS barriers simultaneously.

A consistent effect has been observed with MIS cells on p-base material for which surface etching has been done using 25:10:3 and 1:5:5 compositions of the $\text{HNO}_3\text{:HAc:HF}$ etchant. The former composition produces smooth mid-grain silicon surfaces with some preferential attack at grain boundaries, while the latter yields an overall surface texturing whose morphological detail is grain dependent. Electrically, cells on surfaces etched with the 25:10:3 composition present more tightly distributed behavior in terms of logarithm of I_{photo} vs. V_{oc} characteristics. This suggests that dependence of total diode opposing current on cell voltage and hence the reverse diode saturation current are less variable for the polishing etch.

There has been poor correlation between electrical behavior of the small diagnostic cells used and the density of grain boundaries deduced from preferential etch effects or grain surface morphology. As reported previously for Czochralski-grown polycrystalline material, there is considerable variation in the electrical activity of grain boundaries revealed by chemical means. Furthermore, as stated earlier, with the Wacker SILSO material, the magnitude of maximum photocurrent loss at electrically active grain boundaries is only about 12% compared with values of V_{oc} suppression in Wacker polycrystalline silicon etched to a final thickness of 50 μm gives a conservatively estimated value for the effective minority carrier diffusion length of 110 μm .

While we now have diagnostic cell arrays of various sizes which have given useful information as described above, we feel it is important to conduct grain boundary matrix characterizations using larger area cells. Since grain boundary influences in Wacker SILSO material are so small, even with large area cells it will be necessary to have high performance cells with optimally designed grid electrodes. We have computer modelled grid designs for PN junctions, MIS and inversion layer barriers for a centrally located bus bar.

At Penn State, characterization efforts have involved comparisons of MS and MIS barrier cells on polycrystalline and single crystal material. No etchant-related effects have been noted, but the polycrystalline material produces cells whose dark current behavior appears to be controlled by multi-step tunneling as regards its temperature and voltage dependence.

For the remainder of the program we expect to have the preliminary modeling tasks completed. Prediction of detailed current-voltage behavior for uniform columnar grain material should be possible in terms of grain structural and electrical parameters. Results for photocurrent response to spot excitation as a function of spot-boundary distance and of mid-grain and boundary electrical properties should be

available. Both types of modeling will be exercised over ranges of structural and electrical parameter variation. This will permit assessment of their relevance to actual materials and devices, both for diagnostic purposes and for identification of serious limitations on cell performance.

As regards measurement technique development, lateral sensing of photoresponse should be achieved by the end of the current program if there is timely delivery of the required laser. Preliminary comparisons with photocurrent response should be available for specimens given specific surface treatments.

Through the remainder of the present program, characterization efforts will focus on using sequential slices of Wacker SILSO material. This will permit direct comparisons of barrier processing or heat treatment influences on the behavior of cells having nearly identical detailed grain structure. Cells of 1 cm^2 area will be used to allow inclusion of sufficient grain boundaries to influence opposing current. Conservative grid designs will be used to minimize sheet resistance degradation of fill factor. Small diagnostic cells, whose $\ln I_{\text{photo}}$ vs. V_{oc} behavior has been found to be sensitive to etchant composition at Westinghouse will be examined in more detail at Penn State. This may provide an association between current transport mechanisms (e.g., the suspected presence of multi-step tunneling) and cell processing or treatment.

2. ACHIEVEMENTS ON PRESENT PROGRAM

2.1 Objective

The objective of this program is to understand fundamental aspects of grain boundary influences on photocurrent collection and opposing current transport in polycrystalline silicon cells. Results of the program are expected to aid in optimizing thin film polycrystalline silicon solar cells. Such cells are being considered as a means of meeting the goals of 10% efficiency or greater at module prices below \$0.50 per peak watt (in 1980 dollars).

2.2 Approach

Three major tasks are addressed in this program, which includes a subcontract to the Pennsylvania State University (Penn State). These are: modeling, measurement technique development, and characterization and control of grain boundaries in polycrystalline silicon.

2.2.1 Modeling

Modeling involves an approach which takes two complementary routes. The major effort at Penn State will emphasize treatments of photocurrent collection, photocurrent loss, and bucking current mechanisms for uniform flood illumination with monochromatic or natural solar light. The purpose of this is to develop a comprehensive model of the dark and appropriately illuminated current-voltage behavior of cells in polycrystalline material and to determine the sensitivity of behavior to geometric and electronic parameters.

At Westinghouse, details of photocurrent collection for conditions of spot generation will be modeled. The purpose of this is to determine the accuracy with which values of diffusion length, surface

recombination velocity and grain boundary recombination velocity can be deduced from appropriate measurements. It is planned to use numerical methods similar to those used for determining electrical or magnetic field distributions for two-dimensional situations.

2.2.2 Measurement Technique Development

In measurement technique development the focus is on devising and demonstrating a method by which the uniformity and value of pertinent electrical parameters in large areas of material can be measured. Although measurements of this type can be done on completed cells, it is desired to avoid the fabrication of large area collecting barriers. Such processing can perturb the parameters of interest and/or preclude the assessment of post-barrier treatments. The PSU approach is to sense the lateral photoresponse, either by means of photovoltage or photo-related changes in lateral resistance. Results are to be compared with those obtained using conventional photocurrent collection by an overlying barrier.

2.2.3 Grain Boundary Characterization and Control

For grain boundary characterization and control a matrix of materials and processes is to be investigated at Westinghouse. Processes covering a wide range of temperatures are available at Westinghouse for barrier formation, grain boundary (g.b.) treatment and back surface field preparation. The interactions of selected processes on single crystal and polycrystalline material will be investigated empirically. Results of modeling and measurement technique efforts will be applied to extract cell performance and basic parameter dependences on the various matrix elements of interest.

2.3 Current Status

2.3.1 Cell Modeling

A model has been developed at Penn State to give the current-voltage behavior of a cell formed in a cylindrical columnar grain.

Figure 1 shows a cross-sectional view of the idealized grain. Three regions are identified by the penetration of the front barrier and the back contact into the grain, part way along the grain walls. In the mid-grain region grain boundary recombination is permitted. A different recombination velocity is associated with the wall contacting the back surface.

Fig. 1 Idealized grain, grain-boundary structure analyzed.

For definitiveness we assume the p-type grain shown in Figure 1, which has an N^+ junction at the top. The minority carrier distribution n' satisfies

$$\nabla^2 n' - \frac{n' - n_{p0}}{L_n^2} = -\frac{\alpha K}{D_n} e^{-\alpha(d_F + d_M - z)} \quad (1)$$

where the usual definition of the symbols is used. Here ∇^2 is the Laplacian operator in cylindrical coordinates.

The solution to Equation (1) must satisfy the boundary conditions in Figure 1. Since Equation (1) and the boundary conditions are linear, superposition is valid. Consequently this system is solved first for n in the dark with the voltage V applied to the top junction and then again for short circuit conditions. The total solution is the sum of these two. Solutions for each of the regions in Figure 1, with appropriate matching of functions at their common surfaces, are found containing Bessel-Fourier series.

With proper treatment of the functions, the diode bucking current can be obtained and written in the form

$$I_{Bk} = \frac{q D_n n_{po}}{\tau_{eff}} [\exp(V/kT) - 1] \quad (2)$$

Here τ_{eff} is an effective lifetime determined by the analysis outlined. The value of τ_{eff} , dependent on grain boundary properties and geometry, can be extracted from numerically treating the system of equations produced by the analysis. A bucking current component of the form of Equation (2) has been *assumed* in Reference 1 in analyzing polycrystalline cells. The analysis done on this program *proves* this is valid - at least for columnar grains.

The result of the analysis gives short circuit current of the form

$$I_{SC} = \gamma K \left[1 - e^{-\alpha(d_F + d_M + d_B)} \right] \quad (3)$$

where γ is a collection factor. This γ is determined by the analysis just outlined. It follows from the above that γ is *not* simply the γ of a one-dimensional analysis modified by using τ_{eff} as has been suggested in Reference 1.

This work has resulted in an analytical solution for the I-V characteristics of an n/p solar cell in a columnar grain of material. The model allows for a variable penetration depth of front and back surface-related barriers or contacts and for a mid-grain region having any value of grain boundary recombination velocity. Performance prediction studies can now be undertaken by numerically evaluating the truncated Bessel-Fourier series to yield the excess minority carrier density within the grain.

At Penn State thin silver Schottky devices were fabricated on Wacker SILSO polycrystalline silicon, phosphorus-doped, with a resistivity of 2-3 $\Omega\text{-cm}$. Several etchants were investigated, but they produced no significant differences in cell behavior. (Only about 16 μm of silicon were removed for these cells, as contrasted with 100 μm in the examples above, for which etchant influences were noted.) Characterization of the temperature dependence of current-voltage behavior was made to temperatures of about 130°C. For polycrystalline material, inferred values of diode ideality factor ranged from 2.80 (at 130°C) to 3.78 (at 30°C), while for single crystal material the value was consistent at 1.20. The behavior of the polysilicon devices departs significantly from the thermionic emission character of the single crystal units. A significant portion of the forward I-V behavior for the polysilicon cells (shown in Fig. 2) has the form

$$I = I_S e^{\frac{AV}{e}} e^{\frac{BT}{e}}.$$

The exponential dependence on temperature of the voltage-independent portion of the diode current is like that expected from a multi-step tunneling mechanism. This type of behavior might occur if there is inadequate removal of damaged silicon at the cell surface. More experimental work is needed to explore this phenomenon.

Fig. 2. I-V characteristics of Ag-polysilicon device showing parallel linear regions for varying temperatures.

2.3.2 Measurement Techniques

At Penn State a sample stage has been obtained. This has been used with a focused white light spot to obtain preliminary lateral photovoltage response data on Wacker polycrystalline silicon material. The light spot size and intensity are inadequate for obtaining good quality data at this time. Use of either a He-Ne or a Krypton laser source, both of which have been ordered, is expected to solve these particular problems.

In the meantime, at Westinghouse scanned laser light spot evaluation of MIS barrier devices on Wacker material has been done. In Figure 3(a) and (b) are shown reflected light and photocurrent images, respectively, obtained by scanning a He-Ne laser light spot over an MIS cell ($\text{Al}/\text{SiO}_2/\text{pSi}$) formed on etched Wacker SILSO material. Several grain boundary etch features appear (upper left corner) in the reflection image of the cell. Only one, originating from the upper part of the grid finger at the left, produces significant photocurrent suppression to appear in the photocurrent image of Figure 3(b). A horizontal line scan (Fig. 3(c)) made just above the grid fingers indicates that the maximum photocurrent suppression in this case is about 12%. Similar results were obtained on other cells formed on this material. Earlier, the polycrystalline Czochralski and dendritic web material, we found as much as 30 to 40% maximum suppression at some boundaries (Ref. 2). We believe the current results may reflect use of very high quality starting material in the preparation of Wacker SILSO.

With this ability to characterize grain boundary activity using MIS cells, we will supply material of nearly identical detailed grain structure to the Penn State group for their assessment using lateral sensing of photoresponse. Comparisons of results for boundaries of various electrical activity, before and after heat treatments simulating barrier formation, are planned under the current program. This should allow assessment of the quality and practical utility of the laterally sensed photoresponse data.

(a)

(b)

(c)

Fig. 1 (a) Reflection image, (b) photocurrent image and (c) single scan photocurrent amplitude trace for scanned He-Ne excitation of an MIS cell on Wacker SILSO material.

2.3.3 Grain Boundary Characterization

At Westinghouse grain boundary characterization efforts have been focused on base-line material preparation and cell fabrication. Material preparation efforts have involved a study of grain and grain boundary etching behavior. Use of a rotating beaker apparatus and a nitric:acetic:hydrofluoric acid mixture in the ratio of 25:10:3 has produced surface finishes on Wacker SILSO polycrystalline silicon similar to those previously observed for Dow Corning polycrystalline silicon. This technique results in significant delineation of various twin and grain boundary surface features while producing relatively smooth grain surfaces. Since preferential grain boundary attack may effect solar cell performance, several other etch compositions were explored. Mixtures of HNO_3 :HAc:HF in the following ratios were used: (1) 1:1:1, (2) 1:1:2, (3) 1:2:2, (4) 1:5:5, (5) 1:10:10, (6) 5:9:9, (7) 5:5:1 and (8) 25:10:3, followed by Sirtl etch.

A 1:1:1 composition produces a surface smoothness nearly comparable to that for the 25:10:3 mixture while grain boundary delineation, by comparison, is reduced somewhat. There is, however, a tendency to produce etch pitting of the intra-grain regions using the 1:1:1 formulation. The 1:2:2 and 1:1:2 formulations produce similar surfaces with very slight grain boundary and differential grain etching having intra-grain regions which are very slightly textured. A 1:5:5 composition results in a finely textured (matte) surface with little grain or grain boundary delineation. A 5:5:1 composition produces surfaces which are generally similar to, though somewhat less matte than, 1:5:5 surfaces. A 1:10:10 composition gives variable results. In this case, there is a tendency to produce staining of the surface, presumably due to the HF. The most severe grain boundary delineation was observed (as expected) using a 25:10:3 etch followed by a Sirtl etch.

Some interesting etch-related differences were found in illuminated I-V behavior of $\text{Al}/\text{SiO}_2/\text{pSi}$ cells formed on Wacker material. Use of the 25:10:3 polishing etch resulted in cells whose behavior, in

terms of logarithm of I_{photo} vs V_{oc} (obtained by varying the illumination intensity), was much more tightly distributed than in the case for cells made using a 1:5:5 texturing etch. An example of the comparison is shown in Figure 4. In this case small area cells formed in two sequential slices of Wacker material having nearly identical grain structure. Other groups of cells on the same wafers show somewhat greater variations in behavior, but in any comparison the cells formed on the 1:5:5 etched material always exhibit a larger range of variation.

Figure 5 shows examples of the surface finishes produced by the two etches described and grain boundary delineation. In this case the cells (whose grid electrodes are visible in the micrographs) were formed in regions of closely associated wafers having highly similar grain features. Use of correlated wafers of this type should permit more definitive assessments of cell processing and heat treatment effects on grain and grain boundary behavior in this Wacker material. This compensates in part the disadvantage of the very large grain sizes in the material. The sizes are so large that special care must be taken to detect grain boundary influences on cell performance.

Fig. 4. Comparison of the photovoltaic response of MIS solar cells fabricated on structurally similar Wacker polycrystalline silicon as influenced by the composition of the HNO_3 :HAc:HF etch.

(a)

(b)

Fig. 5. Micrographs of MIS cells formed on Wacker SILSO wafers of similar grain structure but given surface preparation etches in $\text{HNO}_3\text{:HAc:HF}$ solutions of (a) 25:10:3 and (b) 1:5:5 composition.

Using an $\text{HNO}_3\text{:Hac:Hf}$ etch composition, developed earlier in the program, we have thinned Wacker SILSO material to $\sim 50 \mu\text{m}$. We have simultaneously fabricated MIS cells on Wacker material thinned to $50 \mu\text{m}$ and $125 \mu\text{m}$. Both sets of samples had ohmic back contacts. By replotting information taken from Reference 3*, we have constructed the universal curve shown in Figure 6. The curve gives the difference in open circuit voltage values to be expected between a cell with a very thick base region and cells of arbitrary substrate thicknesses (t) normalized with respect to L_n , the minority carrier diffusion length for p-base silicon.

Using this curve and the measured average V_{oc} values for cells in thinner Wacker SILSO material gives a conservatively estimated value of $110 \mu\text{m}$ for the minority carrier diffusion length in this material.

This high value of L_n , coupled with relatively low photo-current suppression and large grain size, has complicated execution of the matrix studies of this program. In order to circumvent this complication we have relied on the ability to identify correlated slices of Wacker material taken in sequence from the original cast ingot. For the remainder of the program it is believed that correlated material will provide a basis for matrix studies by providing a number of substrates of very similar grain structure and thus properties.

While we now have diagnostic cell arrays of various sizes which have provided useful information, we feel it is important to conduct grain boundary matrix characterized using larger area cells. Due to the high quality of Wacker SILSO material, we feel it is necessary to have high performance cells with optimally designed electrodes. Cells of 1 cm^2 area having optimized grid metallization geometry have been designed for N^+P , MIS and inversion layer junctions. These designs use a central bus bar. Cell performance has been computer-modelled in terms of active area losses for each type of collecting barrier. This includes losses due to the sheet resistance of the thin semi-transparent aluminum for MIS cells, of the N^+ layer for N^+P junctions and of the

*Figs. 55 and 57 in Ref. 3.

Fig. 6. Universal curve for open circuit voltage suppression versus ratio of sample thickness to minority carrier diffusion length applicable for L_n 52 to 232 μm .

surface inversion layer in the inversion layer barrier. We have also treated losses due to shadowing and to current flow along both the resistive grid fingers and the central bus bar.

Curves of cell efficiency versus number of grid fingers have been plotted for each type of collecting barrier. In each case we have also treated metallization thickness, grid finger width and incremental bus bar width changes between grid fingers. There are a number of combinations of finger width, spacing, metal thickness and bus bar taper parameters which give similar peak conversion efficiency. For the 1 cm x 1 cm cells considered, the largest single power loss is due to grid finger and bus bar shadowing. One example of computer generated curves for 1 cm² MIS cells is shown in Figure 7. Values for approximately 70Å of aluminum in the barrier structure are used in these calculations and bus bar effects are ignored. Note that near optimum efficiency is predicted for 6 to 7 fingers/cm and reduction of finger width below 2 mils ($\sim 50 \mu\text{m}$) is not advantageous. Note also that peak cell efficiencies are low ($\sim 10\%$) for 70Å of aluminum.

Optimum efficiency as a function of the barrier aluminum film thickness has not yet been included in the modelling but we estimate that $\sim 40\text{--}50\text{\AA}$ may be ideal. In this use optimum conversion efficiency is expected for higher value of grid finger density and for narrower finger width.

In Figure 8 we show the curve for 1 mil finger width of Figure 7 and include the resistive and shadowing losses associated with the presence of a bus bar. In this case, the bus bar is tapered with its width incrementally increased at each point of intersection with a grid finger by the amounts shown. The best trade-off for this particular example occurs at between 2 and 3 mils incremental increase in bus bar width. For the PN junction cell, current flow in the bus bar comprises the second largest power loss while current flow in the active area represents the smallest power loss. In this cell structure, aluminum metallization thickness should be at least 2 μm .

Fig. 7. Predicted MIS cell efficiency for a $70\text{\AA}$ thick aluminum barrier layer vs. number of grid fingers for various grid finger widths.

Fig. 8. Predicted MIS cell efficiency including shading and resistance losses of tapered bus bars, for a $\sim 70\text{\AA}$ thick aluminum barrier layer with grid fingers of 1 mil ($25\text{ }\mu\text{m}$) width.

For the MIS solar cell, there is close correspondence with the PN junction cell for semitransparent aluminum thicknesses in the 80-100Å range, where sheet resistance values of the metal and the diffused layer are comparable. However, the overall efficiency is lower since the optical transmission of 80-100Å of aluminum on silicon is quite low. For this particular example the dependence of cell efficiency on grid finger and bus bar thickness is not as strong as for the PN junction case and 2 μm thick grid metal is adequate.

The inversion layer cell includes effects associated with both high photocurrent and high surface sheet resistance. Current flow in the surface inversion layer is the second largest source of power loss for grid fingers of 25 μm or greater width. In this case, grid finger and bus bar thicknesses of 2 μm or greater are required. The number of grid fingers for optimum conversion in a 1 cm x 1 cm cell is 35. For narrower grid fingers it is interesting to note that the predicted conversion efficiency for an inversion layer cell approaches within about 1% of that for a PN junction cell. We expect to model optimized interdigitated grid geometries and compare results with those for central bus bar geometries. It is felt that a single structure for measuring solar cell characteristics and surface sheet resistance is desirable.

3. PROJECTED EFFORT ON CURRENT PROGRAM

3.1 Modeling

By the end of the current program, modeling of photocurrent response for light spot excitation will be completed at Westinghouse. Results of numerical methods for simple geometries and boundary conditions will be compared with analytical forms in the literature. Results of the numerical approach will be extended to treat noncolumnar grains. Assessments will be made of the behavior of current collected at a surface barrier as a function of the spot-grain boundary distance in terms of sensitivity to mid-grain diffusion length and grain boundary recombination velocity.

At Penn State, the modeling of cells in single columnar grains (described in Section 2.3.1) will be extended to include effects of horizontal grain boundaries. In addition, effort will be applied to treat grains with main axes off-normal to the top surface. Both modifications, if successful, should be useful in treating some practical polysilicon materials.

3.2 Measurements

At Penn State, receipt of the laser sources will complete the lateral photoresponse apparatus. A He-Ne laser and a Krypton variation wavelength (0.33 μm to 0.86 μm) laser have been oriented. The apparatus will be used to compare capacitive photoresponse, lateral open circuit photovoltage and laterally measured photoconductivity for various polycrystalline silicon materials: dendritic web, Wacker SILSO and others as time permits. In particular, specimens supplied by Westinghouse with grain structure detail nearly identical to that for which etch influences have been noted on MIS cell behavior (Section 2.2.3) will be examined for possible correlation with the cell results.

3.3 Grain Boundary Characterization and Control

At Westinghouse, use will be made of sequentially ordered sheets of Wacker SILSO to determine if close duplication of grain structure influences can be verified. To aid in this, large area cells (1 cm x 1 cm) will be used to accommodate the large grain size in this material. Both inversion layer and p-n junction barriers will be used, the former because they can be processed at low temperatures to minimize undesirable heat treatment influences on grain boundaries. Modeling results indicate that 35 aluminum grid lines of 25 μm width (and 0.5 μm thickness) should allow achieving above 14% efficiency in high quality material. Thus, this structure should be more than adequate for evaluation of moderate to large grain polycrystalline silicon. In addition to the optimized grid designs having a central bus bar geometry, we expect to model to model optimized interdigitated grid geometries. It is felt that a single structure for measuring solar cell characteristics and surface sheet resistance is desirable. Predicted performance will be compared with our central bus bar geometries. Cells in which interesting process or heat treatment influences on photovoltaic behavior are found will be examined for details of photocurrent collection with scanned laser spot excitation. They will be sent then to Penn State for further evaluation, particularly as regards identification of current transport mechanisms.

We also expect to produce cells at Westinghouse on polycrystalline material thinned to 50 μm or less by appropriate etching. Some preliminary results have been obtained already on 50 μm material using AR-coated MIS cells. Comparisons with 125 μm thick cells in terms of open circuit voltage performance indicate an effective diffusion length of about 110 μm in the Wacker material used. Such cells should be adequate for preliminary studies of back surface field influences which will also be undertaken.

For the matrix studies of this program, the consistency of barrier behavior from lot to lot is crucial considering the small changes in detailed cell behavior anticipated on the basis of the previous

discussion. Intuitively, it is felt that MIS barriers produced at low temperatures are well suited for such characterizations. We plan to study the reproducibility of MIS barrier formation by repetitively reprocessing and characterizing cells on the same substrate.

At Penn State, experimental work will be continued to identify, if possible, the source of the multi-step tunneling-like behavior of the polysilicon cells. In particular, effects of extensive etch removal of silicon will be explored to determine if surface damage is involved.

4. SUGGESTED FUTURE WORK

4.1 General Approach

Successful completion of the present program is expected to provide a good foundation for measuring and understanding some basic grain boundary influences in a reasonably high quality polycrystalline silicon material, e.g. Wacker SILSO or polycrystalline dendritic web. An important second step involves assessment of the role of electronically active, undersirable impurities. These impurities may be encountered in candidate materials for low cost, thin film polycrystalline silicon solar cells. We think it is appropriate to shift to Czochralski polycrystalline material which has been successfully doped with titanium (Ref. 4, pp 90-94). At least two and preferably three types of material should be used: base-line p-type material with no Ti, material lightly doped with Ti ($\sim 10^{13} \text{ cm}^{-3}$), and material heavily doped with Ti ($\geq 10^{14} \text{ cm}^{-3}$). Although some preliminary characterization of p-n junction cells in Ti-doped polysilicon has been done at Westinghouse, its scope was limited to performance evaluation of a single lot of cells and some preliminary DLTS examinations.

For the proposed program, we would extend the base-line effort of the first year program into the new material area, as detailed in Section 4.2. Comparisons would be drawn between the Wacker material and the CZ polysilicon with and without deliberate Ti impurities. This should provide useful insights into impurity mechanisms in various technologically attractive materials which may be considered in the future.

4.2 Specific Suggested Tasks

4.2.1 Task 1: Modeling

At Penn State, modeling efforts should be extended to arbi-

trarily shaped grains. A Green's function approach should be used and initially tested by comparison with the Fourier-Bessel series results. Methods for treating an assembly of grains having a distribution of sizes should be explored.

4.2.2 Task 2: Measurement Techniques Development

At Penn State, refinement of the apparatus and theoretical interpretation of measurements should be the focus of the effort. Capacitively detected photoresponse, open circuit photovoltage, and photoconductivity data should be taken on polycrystalline silicon materials, compared, and interpreted. The attributes, disadvantages, and meaning of the data generated by each of these measurements should be determined. The desirability for using transparent layers (ITP) on polysilicon to enhance carrier collection should be determined.

At Westinghouse, the method of Deep Level Trap Spectroscopy (DLTS) should be examined as a means of quantifying the density of traps associated with deliberate introduction of titanium as an impurity. In particular, the method of Spencer et al. applied in polycrystalline GaAs (Ref. 5) should be tried. With this method, ohmic contacts applied to either side of a grain boundary allow using the depletion regions on either side of the grain boundary to sense the DLTS signal. In this way, sensitivity to the grain boundary effects is enhanced by eliminating signals associated with an overlying surface barrier.

4.2.3 Task 3: Grain Boundary Characterization and Control

At Westinghouse, effort on this task should be applied to extend the results obtained on Wacker SILSO material to Ti-doped polycrystalline CZ silicon.

Thin film polycrystalline silicon material should be simulated either by chemical etching or by beam milling of the back surface after formation of the collecting barrier. Chemical etching has been successful in preparing material of $\sim 50 \mu\text{m}$ thickness which has demonstrated reduced V_{oc} behavior due to back contact recombination. This simulation, particularly with Ti-doped material, should be valuable in assessing the

effectiveness of back surface field action in potentially low cost thin film polycrystalline cells.

As in the original program, a matrix study of several promising barrier formation, grain boundary passivation, and back surface field region processing methods would be examined. Specifically ion implantation, solid state and gas source diffusions, and hydrogenation should be considered and applied, as appropriate, to Ti-doped polysilicon as well as to relevant control samples.

At Penn State, cells using ITO layers to reduce the sheet resistance of the top layers in M-S, MIS and homojunction barriers should be evaluated. Such devices should also be useful for correlation of device behavior with modeling predictions and with the lateral photosensing techniques.

5. REFERENCES

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