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THIN FILM POLYCRYSTALLINE SILICON SOLAR CELLS

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MASTER

By

Amal K. Ghosh, Tom Feng,
Daniel J. Eustace, and H. Paul Maruska

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PATENT STATUS

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OBJECTIVES

The objectives of the project are: 1) to develop cell fabrication procedures to further define the maximum capabilities of the conducting oxide/silicon heterojunction solar cells; 2) to optimize the spray fabrication technique for making reproducible high efficiency cells; 3) to assess the stability and the projected lifetime of the cell structure; 4) to identify through appropriate measurements the effects of grain boundaries and intragrain defects on the electronic transport mechanisms in thin-film polycrystalline silicon; and 5) to determine the feasibility of a large-scale fabrication process.

PREFACE

This is the first quarterly report of progress on work performed for SERI under subcontract No. XJ-0-9077-1. The period covered is from April 15 to July 15, 1980. The report is divided into the following three categories.

- Cell Fabrication
- Stability of Solar Cells
- Properties of Polysilicon Materials and Device
Modelling of Solar Cells

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THIN FILM POLYCRYSTALLINE SILICON SOLAR CELLS

1. SUMMARY

During the present quarter efficiency of heterostructure solar cells has been increased from 13 to 13.7% for single crystal and from 10.3 to 11.2% for polysilicon. For polysilicon the improvements can be attributed to reductions in grid-area coverage and in reflection losses and for single crystal to a combination of reduction in grid-area coverage and increase in fill factor. The heterostructure cells in both cases were $\text{ITO}/\text{n-Si}$ solar cells.

Degradation in $\text{SnO}_2/\text{n-Si}$ solar cells can be greatly reduced to negligible proportions by proper encapsulation. The cells used in stability tests have an average initial efficiency of 11% which reduces to a value of about 10.5% after 6 months of exposure to sunlight and ambient conditions. This small degradation occurs within the first month, and the efficiency remains constant subsequently. The reduction in efficiency is due to a decrease in the open-circuit voltage only, while the short-circuit current and fill factor remain constant.

The effects of grain-size on the Hall measurements in polysilicon have been analyzed and interpreted, with some modifications, using a model proposed by Bube. This modified model predicts that the measured effective Hall voltage is composed of components originating from the bulk and space-charge region. For materials with large grains, the carrier concentration is independent of the inter-grain boundary barrier, whereas the mobility is dependent on it. However, for small grains, both the carrier density and mobility depend on the barrier. These predictions are consistent with experimental results of mm-size Wacker polysilicon and μm -size NTD polysilicon.

2. CELL FABRICATION

The over-all goal of the present program is to fabricate 12% efficiency polysilicon solar cells with areas $\geq 20 \text{ cm}^2$ by the spray deposition process. To achieve such a goal, there are some intermediate milestones. The one for this quarter is to fabricate smaller area cells (1 and 4 cm^2) with efficiency of 11% for diffused or heterostructure cells using polysilicon and 13% heterostructure cells using single crystal silicon. By heterostructure cells we mean $\text{SnO}_2/\text{n-Si}$ and $\text{ITO}/\text{n-Si}$ solar cells made by spraying; by diffused cells we mean only p on n cells. Although there are many reports of n on p diffused polysilicon cells, we believe ours is the only work reported for p on n cells.

The power curves of our best single crystal and polycrystalline $\text{ITO}/\text{n-Si}$ solar cells are shown in Figs. 1 and 2, respectively.

For cell fabrication, we have used four different batches of material. All batches do not give the same results. The data shown in Tables I and II are for the best cells. For the cells made from the best batch of material, the efficiencies are very close to the theoretical values. The efficiencies of diffused cells fabricated during this reporting period remain about the same as those reported in our previous contract. For 1-mm grain-size silicon, the theory we developed for polysilicon solar cells predicts a short-circuit photocurrent of $30 \text{ mA}/\text{cm}^2$ and an open-circuit voltage of 0.54V. The measured J_{sc} is of the magnitude of the predicted value in spite of the fact that there are still some losses due to grid coverage and reflection. The measured open-circuit voltage is slightly higher ($< 5\%$) than the predicted value. These results suggest that the theory of polysilicon solar cells needs to be modified. However, the modification would be small; perhaps one that leads to

FIGURE 1

FIGURE 2

Table I

Solar Cell Parameter		Polysilicon N-Type Wacker 1mm Grain			
	Theory	ITO/n-Si		SnO ₂ /n-Si	p/n
Area (cm ²)		1	4	4	4
J _{sc} (mA/cm ²)	30	29.8*	27.7	26.6	27.3
V _o (V)	0.54	0.557	0.55	0.56	0.53
Fill Factor	0.78	0.67	0.702	0.68	0.71
Eff. (%)	12.5	11.2	10.7	10.1	10.3

* Fewer grid lines

Table II

Solar Cell Parameter	Single Crystal N-Type Heterostructure							Diffused
	ITO/n-Si		SnO ₂ /n-Si				Theory	p/n
Area (cm ²)	4	4	4	4	20	20		4 cm ²
J _{sc} mA/cm ²	26.0	30.2 *	29.0	29.1	25.13	27.5	36.5	28.3
V _{oc} (V)	0.604	0.626	0.615	0.615	0.595	0.605	0.65	0.585
Fill Factor	0.77	0.73	0.68	0.685	0.64	0.58	0.84	0.765
Eff. (%)	12.1	13.74	12.1	12.3	9.56	9.7	20.25	12.7

* Fewer grid lines

changes in the device parameters of less than 10 percent. In formulating the theory many assumptions were made to make it simple. For example, it was assumed that the grain-boundary density of states is constant, and those grain boundary states that act as recombination centers have a density of about $1.6 \times 10^{13} / \text{cm}^2 \text{eV}$. The recent result reported by Faughnan of RCA indicates that the grain boundary recombination velocity for bicrystal is less than that for Wacker polysilicon, which is smaller than that of Honeywell's polysilicon on ceramic. This result can be interpreted on the basis that the densities of recombination levels in the grain boundaries are different for the various materials. Even for the same material the density of grain boundary states can change by a factor of 2 or more by heat treatment or varying fabrication parameters. It is very difficult to predict the efficiency for a material with a particular grain-size to a factor better than 10 percent. We feel if the number of grain boundary recombination states in Wacker polysilicon were lower than $1.6 \times 10^{13} / \text{cm}^2 \text{eV}$, as assumed in our theory, then J_{sc} , V_{oc} and F.F. values could be slightly higher than those predicted.

The improvement in efficiency for polysilicon cells in the present quarter can be attributed mainly to reductions in the area of grid coverage and reflection losses, and for single crystal cells, to a combination of reduction in area of grid coverage and increase in fill factor. Because ITO films have lower sheet resistance than that of SnO_2 , ITO/Si cells require less grid lines. We feel our present grid pattern has not been optimized; therefore further improvement in the short-circuit current may be possible by designing a grid pattern that "matches" the sheet resistance.

3. STABILITY STUDIES

In the past we have reported that SnO_2/Si cells can show degradations in efficiency by as much as 10 - 15%, depending on the environment in which the cells were kept and on encapsulation techniques. These losses in efficiency were the result both of decreases in V_{OC} and in fill factor. For example, progressive corrosion of the wiring used on early encapsulated cells was responsible for a portion of the efficiency loss. Also, unencapsulated cells exposed to moisture in the air were found to suffer decreases in both V_{OC} and FF that exceeded the losses encountered in protected cells. Our earlier studies had indicated that the losses in performance were a result of a combination of several processes which apparently involved the electrodes, the SnO_2 , and the SnO_2/Si interface. The present studies have been designed in a manner such that these roles might be separated. Our current work has served to confirm our contention that losses in efficiency can be minimized to less than 5% in properly protected cells. We are monitoring the parameters of our test cells on a regular schedule, and we have both cells which have soldered leads and an encapsulant, as well as cells without wiring held in a partial vacuum. We find that in either case, cells which start out with an 11% efficiency stabilize at 10.5% after a month in sunlight.

More extensive facilities have now been set up for studying the stability of solar cells. Some of the cells are on the roof and the others near windows. Glass tubes have been mounted behind a south-facing window, and partial vacuum is maintained in them with a mechanical pump. The choice of location has been dictated by the capability of maintaining

a vacuum in the tubes. Cells are kept on teflon trays in these tubes, and they are removed on a regular schedule for testing in AM1 simulated sunlight. At present, we have 37 $\text{SnO}_2/\text{n-Si}$ sprayed cells, 3 $\text{ITO}/\text{n-Si}$ sprayed cells, 10 p/n diffused single crystal cells, and 4 p/n diffused polysilicon cells under test in these tubes.

There are also sets of cells under test which are encapsulated in silicone rubber and have soldered wiring attached. One set of 6 (2 $\text{SnO}_2/\text{n-Si}$ single crystal, 2 $\text{SnO}_2/\text{n-Si}$ polysilicon, 2 p/n diffused polysilicon) has been outdoors on the roof in Linden since November 5, 1979. This set of cells was not provided with solid protection (i.e., glass cover) for the encapsulation, and consequently degradation in performance attributable to weathering of the potting compound is being observed. A second set of ten encapsulated cells has now been placed behind a glass shield, also on the roof. The degradation of exposed silicone rubber is a direct consequence, of course, of the action of dust and sand when a glass shield is lacking. The set of glass shielded, potted cells include 6 sprayed $\text{SnO}_2/\text{n-Si}$ single crystal, 3 sprayed $\text{ITO}/\text{n-Si}$ single crystal, and one sprayed $\text{ITO}/\text{n-polysilicon}$.

The cells in the vacuum tubes, which are fully exposed to sunlight in a south facing window, were fabricated from a number of different wafers, and therefore various individual cells have been under test from between 75 to 120 days. Diffused p/n junction cells, whether single crystal or polysilicon, show no measurable changes in V_{oc} , where our detection limit is 0.1%. J_{sc} , FF and hence Eff are much more strongly dependent on light intensity than V_{oc} is, and small random fluctuations in intensity for a solar simulator system are difficult to control beyond about 2 or 3%. However, with a large number of measurements over a long time period of

testing, these fluctuations average out. At this time we see no changes in the average J_{SC} , FF or Eff for diffused cells.

The above comments about random fluctuations in J_{SC} from test to test also apply to spray deposited cells. For example, Figure 3 shows the measured short circuit currents for 3 representative sprayed $SnO_2/n-Si$ single crystal cells over a 120 day period. It is very obvious from the figure that on average there is no change in the currents. This conclusion applies to all of the sprayed cells, including ITO cells.

The open-circuit voltages of the cells tested lie within a band of $\pm 3\%$ of .595V. Individual cells sometimes show small decreases in V_{OC} , never more than 2 or 3%, which occur within the first 40-50 days of operation, followed by stable operation. In many cases the slight change in V_{OC} does not affect the maximum power point, resulting only in an apparent increase in FF. We are at present studying dark I-V characteristics to see if this observation can be interpreted.

In summary, then, the average SnO_2/Si cell kept in vacuum and sunlight for 120 days will have $J_{SC} = 29 \text{ mA/cm}^2$, $V_{OC} = 0.595$, FF = 0.62 and an Efficiency of 10.5%. Recent advances in processing are leading to FF in the 0.72 range so that average efficiencies will soon exceed 11%.

A set of 6 encapsulated cells has now been exposed to the environment for more than 225 days. The two p/n diffused poly Si cells have kept constant V_{OC} 's during the periods, but losses in J_{SC} have led to reductions in Eff. The losses in J_{SC} can be attributed to weathering of the potting compound. For the sprayed tin oxide single and polysilicon cells, there have been no changes in V_{OC} 's after losses of about 5% incurred

Figure 3

during the first 30 days of exposure. They also show reductions in J_{sc} due to weathering of the encapsulant.

The second set of potted cells was protected by a glass shield. After 90 days of exposure to sunlight outdoors, we found that open-circuit voltages decreased by 1 to 2% and then stabilized, while short-circuit currents remained constant throughout for these sprayed SnO_2/Si cells. The average efficiency of these cells is 10.5%. Thus these potted cells are equivalent in performance to those kept in vacuum.

3.1 Effects of Processing on Device Performance

A series of experiments were designed to elucidate the effects of variations in the processing procedures, such as prespray treatments and heat treatments, on device performance for sprayed SnO_2/Si cells. Many of the subsequent measurements were made with a point probe contact on unmetallized wafers to avoid complications due to changes in the metallization during the treatments.

All these measurements involved monitoring V_{oc} at a point contact under illumination from an incandescent lamp. Our standard procedure for depositing a tin oxide film on silicon is to simply use the silicon wafer directly as received from the manufacture, without any cleaning. Such cells then always show $V_{oc} = 0.69 - 0.70\text{V}$ with a point contact. We then tried some pretreatments for the wafers. We found that dipping the wafers in water or in concentrated HCl before spraying does not alter the value of V_{oc} . However, all other pretreatments we tried reduced V_{oc} , in some cases dramatically. If the wafer is preheated in air at 425°C for 10 minutes, V_{oc} is decreased by about 30 mV. If during this preheating the surface of the wafer is covered

with powders of either SiO_2 , MgSO_4 , SnO_2 , or NH_4Cl , again, V_{oc} is decreased by 30 mV. This implies that only the heating and not the powders is operative. If, prior to spraying, the wafer is dipped either in conc. HF or in HCl containing Zn dust (so that nascent hydrogen is released), V_{oc} is decreased by 50-80 mV. Preheating with NaOH, NaCl or K_2SO_4 present on the surface reduces V_{oc} by 50% or more.

The SnO_2 film can be removed from the silicon surface by treating the wafer in HCl solution with Zn. If the wafer is then dried and resprayed, V_{oc} will be approximately 0.630, exactly as if it had simply been a new wafer dipped in HCl + Zn. It has proven possible in all cases to etch and spray wafers which were degraded in various ways to bring V_{oc} back to the 0.630 level. For example, by heating a sprayed wafer above 400°C , V_{oc} will be reduced by 50% or more. If the SnO_2 is then etched off and the wafer resprayed, V_{oc} will be 0.630. To recover cells exposed to Na or K, the HCl + Zn etch must be followed by a dip in HF, before respraying. It is interesting to note that we were not able to improve V_{oc} of metallized cells pretreated with Na by applying a reverse bias to drift the Na out. We heated such a cell, which had an initial $V_{oc} = 0.10\text{V}$, at 300°C for 9 hours at -4V with 70 A/cm^2 flowing, and then for 2 more hours at 500°C with the same reverse bias, but after all this time V_{oc} (which was monitored on a regular basis every 2 hours) was only 0.13V.

It should also be stressed that decreases in V_{oc} are not accompanied by decreases in J_{sc} (again measured at a point contact) after heat treatments of unmetallized cells, as long as the back contact is kept clean by etching. For example, one wafer had an initial $V_{oc} = 0.65$, $I_{sc} = 2.7\text{mA}$. After heating at 500°C for 10 min, $V_{oc} = 0.31$, $I_{sc} = 0.25 \text{ mA}$.

However after the back surface (but, of course, not the front) was etched clean, $V_{oc} = 0.31$, $I_{sc} = 3.0$ mA. After an etch ring was formed around the perimeter to avoid leakage across the junction over the wafer edge, $V_{oc} = 0.32$, $I_{sc} = 2.7$ mA. This experiment is not a simple one to repeat with a metallized cell, of course, because the back metal would have to be removed and then replaced. It must be stressed that interpretations of current reductions can be severely confused by back contact problems.

We can see, therefore, that the condition of the thin native SiO_x layer on the Si front surface is critical for device performance. Any procedure which alters this film disturbs V_{oc} . Etching it (HF, HCl + Zn, heating it, or exposing it to alkali metal ions results in losses in V_{oc} .

4. DEVICE MODELLING

4.1 Hall Measurements and Grain-Size Effects in Polycrystalline Silicon

Hall measurements have been reported on polycrystalline silicon by many workers.¹⁻⁷ Although the measurements are straight-forward, the interpretation of such data has generated some controversies.⁶⁻⁸

Many of the measurements were made on materials with grain-sizes $< 1000 \text{ \AA}$,^{1,2,6,7} and Seto's theory, with some modifications,^{6,7} can explain most of the features of these reported results. In spite of the fact that there are disagreements in the details among the different theories proposed, there is general agreement that trapping at grain boundaries creates barriers and affects both free carrier density and mobility measurements. In contrast to these results, we have recently⁹ shown that for polysilicon having a grain-size of about 1mm, the measured free carrier concentration is associated with the bulk of the grain

and is not affected by trapping and the presence of the space-charge region or barrier. However, the mobility is affected by intergrain boundary barriers and the measured value corresponds to an effective mobility. We demonstrated that light reduces or even eliminates the barriers and the variation of Hall mobility with temperature (with the barriers removed) was very similar to that of single crystal. Thus from such measurements, one could obtain both effective and microscopic mobilities.

In this report we show that for grain-sizes of the order of $10\text{ }\mu\text{m}$, none of the existing theories are applicable. For these grains, the space-charge region is not likely to extend across the whole grain even at low doping densities. However, the Hall-measurement results in these intermediate grain-size materials appear to be similar to those observed for small grain-size material in which the grains can be fully depleted. The reason this occurs is that the Hall voltage in $10\text{ }\mu\text{m}$ grain size material arises from contributions due both to the bulk and to the space-charge regions, the contribution from the latter being larger. These results can be understood on the basis of Rube's theory of Hall-effect measurements in inhomogeneous materials.¹⁰ To explain Hall and photo-Hall results in inhomogeneous materials such as, for example, thin films of PbS, Bube proposed a simple model. The model consists of considering the materials as made up of particles of dimension ℓ_1 and resistivity ρ_1 , separated by interparticle regions of dimension ℓ_2 and resistivity ρ_2 , as illustrated in Figure 1(a).

After making some modifications, we have extended this model to explain results on polycrystalline silicon. In our modified model,

we associated ρ_2 and ℓ_2 to the space-charge region (including the inter-grain boundary regions). The equivalent circuit of the basic unit for calculation of the different Hall voltages is shown in Figure 4(b).

The other equivalent circuits necessary to describe the complete results in polycrystalline silicon are also shown. These variations may be treated as special cases. Figure 4(c) is valid for large grains (e.g. 1mm) and Figure 4(d) for small grains (e.g. $\leq 1000\text{\AA}$) where at low dopant concentrations complete depletion effects can be observed. According to Bube's analysis the Hall voltages in the different regions can be expressed as follows:

$$V_1 = R_1 \ell_1 j_1 B = R_1 \ell_1 \frac{V_a}{L} \frac{1+\beta}{\rho_1 + \beta \rho_2} B \quad (1)$$

$$V_2 = R_2 \ell_1 j_1 B \beta = R_2 \ell_1 \frac{V_a}{L} \frac{1+\beta}{\rho_1 + \beta \rho_2} B \beta \quad (2)$$

$$V_3 = R_2 \ell_2 j_2 B = R_2 \ell_2 j_2 B = R_2 \ell_2 \frac{V_a}{L} \frac{1}{\rho_2} B \quad (3)$$

so that the Hall voltage ΔV_H developed across the unit sketched in Figure 1(a) is given by

$$\Delta V_H = V_1 \frac{r_2}{r_1 + r_2} + V_2 \frac{r_1}{r_1 + r_2} + V_3 \quad (4)$$

where $\beta = \ell_2/\ell_1$, $\alpha = \rho_1/\rho_2$, $R_1 = (n_1 e)^{-1}$ and $R_2 = (n_2 e)^{-1}$.

The measured Hall constant R is related to ΔV_H by

$$R = \frac{\Delta V_H}{JB(\ell_1 + \ell_2)} \quad (5)$$

where J is the total current density.

FIGURE 4

(a)

(b)

(c)

(d)

For $\alpha, \beta, \ll 1$, it can be shown that the ratio of the measured free carrier concentration n to that corresponding to the bulk can be expressed as:

$$\frac{n}{n_1} = \frac{1}{1+\beta(1+\beta/\alpha)} \quad (6)$$

and the ratio of the corresponding measured Hall Mobility μ_H to that of the bulk μ_1 as:

$$\frac{\mu_H}{\mu_1} = \frac{\alpha}{\alpha+\beta} + \beta \quad (7)$$

In Equation (7) we have assumed the microscopic mobility μ_1 in the bulk of the grain and the microscopic mobility μ_2 in the space charge region are equal. Through ΔV_H , both n and μ depend on α and β . For $\beta \ll 1$, it can be shown that $V_2 = \beta V_1/\alpha$ and $V_3 = \beta V_1(\alpha+\beta)/\alpha$. For polysilicon of grain size $\sim 10 \mu\text{m}$, the values of α and β are such that the Hall voltages V_2 and V_3 are larger than V_1 . Since V_2 and V_3 are the Hall voltages developed within the space charge region, the measured carrier density is lower than the bulk density. However, with increases in doping, the barrier height and β decrease while α increases. Therefore, the contribution from the barrier region to the Hall voltage is reduced, and one finally measures a carrier concentration approaching the bulk value at higher doping densities.

Recently we¹¹ have shown that the dopant concentration at which the mobility minimum and the sharp increase in free carrier concentration occurs follow approximately the relation

$$N_d \sim 10^{12}/d \quad (8)$$

where d is the grain size in cm and N_d is the doping density. The reported data³ for $25 \mu\text{m}$ NTD (neutron transmutation doped) polysilicon

fit this relation very well; as a result we concluded that Seto's theory was applicable even for 25- μm material. Based on our present understanding, we now believe that the good agreement between Seto's theory and the 25 μm data is accidental. The 25- μm grain size Hall data appear to behave like 1000 $\text{\AA}$ or less data because of contributions from the space charge region. Bube's theory in its modified form can also account for the mobility minimum.¹² In our previous letter we demonstrated that if the light intensity is not too high, photoexcitation results primarily in a reduction of the barrier height. Such reduction decreases ρ_2 and increases α . Thus α is expected to increase with light intensity. From Equations (6) and (7) we see that for $\beta \sim 0.1$ both n/n_1 and μ_H/μ_1 should increase with an increase in α but not necessarily at the same rate.

To test for self-consistency of our model, we have compared the values of n and μ_H determined experimentally with a standard four point probe and Hall Effect apparatus with those predicted by Equations (6) and (7). The measurements were made on polycrystalline silicon obtained from the Monsanto Company. By using appropriate etching techniques we were able to show that the grain sizes of this material vary between 1 and 50 μm ; however about 50 percent of the grains were in the range of a few microns. The theory developed still holds for this grain size distribution. Doping of the material was effected by neutron transmutation doping in the University of Missouri's nuclear reactor. The irradiated material was then annealed according to reported procedures to remove radiation-induced defects.

The predicted values of n and μ_H as shown in Table III were calculated by assuming the following values for β , ρ_1 , n_1 , and μ_1 : $\beta=0.1$, $\rho_1=1$ ohm cm, $n_1 = 4.8 \times 10^{15}/\text{cm}^3$ and $\mu_1 = 155 \text{ cm}^2/\text{V sec}$. The measured sample resistivity and changes in it with light were attributed to changes only in ρ_2 (where we expect greater changes in ρ_2 for larger grains). There was found to be a decrease in the measured activation energy of the resistivity with increasing light intensity. The predicted values of n and μ_H were calculated using Equations (6) and (7). The agreement between predicted and observed values are excellent. These results indicate that, for the particular material studied, the smaller grains are responsible for the Hall voltage, and the values chosen for the different parameters are consistent with our knowledge about the material. From the doping density and measured grain boundary barrier height (from ρ versus $1/T$ curve), λ_2 is estimated to be $\sim 0.17 \text{ } \mu\text{m}$. This suggests that for β to be 0.1, λ_1 has to be $\sim 1.7 \text{ } \mu\text{m}$ which happens to be about the size of the smaller grains. The bulk carrier concentration agrees closely with the value estimated from the magnitude of the neutron flux used in the NTD treatment. However, the 155 cm^2 volt-sec value for bulk mobility is lower than single crystal value for the same doping density. This lower mobility value is in agreement with other data reported for grains $< 25 \text{ } \mu\text{m}$ where barriers were eliminated by doping.^{3,11} The present results along with the other results^{1-3,5} tend to indicate that mobilities in small grain materials are low. It has been reported that the density of

TABLE III
Mobility and Carrier Concentration
As a Function of Polycrystalline Silicon resistivity

ρ (ohm-cm)	α	n/cm^3		$\mu_H(\text{cm}^2/\text{V-Sec})$	
		Predicted	Measured	Predicted	Measured
100	1×10^{-2}	2.28×10^{15}	2.1×10^{15}	29.45	30
87.5	1.1×10^{-2}	2.39×10^{15}	2.3×10^{15}	30.85	31
73	1.3×10^{-2}	2.57×10^{15}	2.6×10^{15}	33.32	33
58	1.7×10^{-2}	2.84×10^{15}	2.85×10^{15}	38.00	37.5

grain boundary states possibly decreases with increasing grain size.^{7,8} Such observations are also consistent with previous studies which have observed low J_{sc} in small grain polysilicon solar cells relative to the theoretically predicted values.¹¹ The possibility of barrier shrinkage with light was invoked to account for the difference.

As reported earlier, we⁹ have found that for polysilicon with large grains ($\sim 1\text{mm}$) μ and ρ vary with barrier height, but n remains constant. The reason for such a result can be understood as follows. For large grain sizes, V_3 can be neglected in comparison with V_1 and V_2 . Accordingly,

$$\Delta V_H = V_1 \frac{r_2}{r_1 + r_2} + V_2 \frac{r_1}{r_1 + r_2} = V_1(1 + \beta^2) \quad (9)$$

Since $r_2 \gg r_1$ and $\beta \ll 1$

$$\Delta V_H \sim V_1 \quad (10)$$

This result suggests that for large grains, the measured or effective Hall voltage should correspond to the bulk of the grain and be independent of the barrier height.

In conclusion we would like to say that Hall-effect measurements in polysilicon can be understood when one can isolate the different Hall voltages to yield information about the relative contributions of the bulk and space-charge regions.

4.2 EPR Studies in Polysilicon

In polysilicon an EPR signal is observed with a g value of 2.0052 ± 0.0005 and a line width of 7-12 Gauss. As an example, a typical NTD silicon whose bulk carrier density has been estimated to be about $4.8 \times 10^{15}/\text{cm}^3$ has the spin density of about $11.8 \times 10^{15}/\text{cm}^3$. The exact value of the

spin density varies from sample to sample by a factor of two or more. For a p-type Wacker Polysilicon sample having a carrier concentration of $3.80 \times 10^{15}/\text{cm}^3$, the g value is about 2.00505, and the spin density $\sim 1.11 \times 10^{15}/\text{cm}^3$. Though the grain-sizes of the two materials differ by about two orders of magnitude, the spin density differs by a factor much less than an order of magnitude. These results appear to indicate that the EPR signal may not be correlated with grain-boundary states. However, more work is needed to obtain a definitive conclusion.

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