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AMORPHOUS Si SOLAR CELLS

Second Quarterly Report

1 April 1979 - 30 June 1979

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Nancy Goodman, H. Fritzsche and H. Ozaki.
- B. "Design Consideration for a-Si Solar Cells", Vikram Dalal.

SUMMARY

This report describes the efforts at the University of Delaware and the University of Chicago during the second quarter of DOE Contract 03-79-ET-23034. The objectives of the program are to study and improve properties of plasma deposited a-Si and to design, manufacture and analyze a-Si devices. The accomplishments during the second quarter are:

1. Material Growth

- Reproducible, stable, films can be grown from SiH_4 plasma. Films are generally free of pinholes or structures.
- Doping studies of n and p type have started.
- Films containing F have been grown from $(\text{H}_2 + \text{SiF}_4)$ mixture.

2. Material Characterization

- Field effect measurements of intergap state densities have been started. A computer program to correctly analyze field effect measurements has been developed.
- Absorption studies show that a-Si:F,H films can have a higher bandgap, and that bandgap can be changed by varying H:F content in the plasma.
- Studies of activation energy of conductivity have started. They show that n-doped a-Si:F,H films can have very high conductivities [$\sim 10 (\Omega\text{-cm})^{-1}$] and very low activation energies (0.023 eV).
- Photoluminescence efficiency has been measured, and found comparable to the efficiency of RCA films.
- Infrared absorption data shows that H is mainly bonded as Si:H and not as Si:H_2 .

3. Device Design

- An analysis of a-Si devices has been completed. The analysis shows that even with limited diffusion length ($0.1 \mu\text{m}$) and high defect density ($10^{16}/\text{cm}^3$), a-Si devices can achieve $J_{sc} \approx 15 \text{ mA/cm}^2$, $V_{oc} \approx 1\text{V}$ and $\text{FF} \approx 0.72$.
- Novel a-Si devices have been designed and analyzed. The analysis shows that the flexibility in material properties offered by a-Si can be used advantageously to design high quality devices.

1. Introduction

a-Si is a promising photovoltaic material. During the second quarter, the University of Delaware and its subcontractor, the University of Chicago, have started detailed work on studying the growth and material properties of a-Si. Optimized device designs have also been carried out for a-Si devices, based on realistic material properties.

This report describes the work done at Delaware and Chicago during the second quarter, 1 April 1979 - 30 June 1979.

II. Material Growth

The growth system described in the previous quarter's report has been used to grow hydrogenated and fluorinated films by decomposing SiH_4 and $(\text{H}_2 + \text{SiF}_4)$ mixtures respectively.

1. Hydrogenated Films

a-Si:H films have been grown at substrate temperatures varying between 250°C and 425°C . All the films were grown on the cathode side of the system so as to avoid the morphology problems described by Knights et al.⁽¹⁾ Films were grown from SiH_4 :He mixtures. The deposition rate typically was $1 \text{ \AA}/\text{sec}$ and typical pressures were in the range 250 mTorr - 1 Torr. The films had no noticeable structure in a SEM scan, had generally low pinhole density, and were uniform in thickness over most of the sample area. A variety of substrates were used, including 7059 glass, 7740 glass, quartz, Molybdenum, 7059 coated with Mo and single crystal Si. Most of the films had a low Si:H₂ bond density as indicated by infrared absorption (Fig. 1). In Fig. 1, there is a very small absorption peak at $\sim 830 \text{ cm}^{-1}$, which is where a SiH₂ band would show up. In contrast, the two Si:H bonds, at 637 cm^{-1} and 2010 cm^{-1} , show strong absorption peaks, indicating that the film has mainly Si:H bonds.

The films were doped n-type by using AsH_3 and p-type by using B_2H_6 . The AsH_3 and B_2H_6 contents were varied from 40 ppm - 5000 ppm in SiH_4 . The doping efficiency is discussed in Section III.

2. Fluorinated Films

Fluorinated films were grown by depositing from $(\text{H}_2 + \text{SiF}_4)$ mixtures.⁽²⁾ Typical substrate temperature was $350 - 425^\circ\text{C}$ and pressure was ~ 1 torr. Below 1 torr, SiF_4 did not decompose. Some fluorinated films had significant residual

Fig. 1.

Infrared Transmission of a-Si:H

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stress and they flaked off, in contrast to the hydrogenated films which almost never flaked off the substrate. We believe this flaking is related to excess F or H incorporation, resulting in a heavily stressed film,⁽³⁾ and we are working on solutions to this problem which would reduce the stress in the film.

A striking result of fluorinated films is that the bandgap can be varied over a rather wide range (1.6 - 2.0 eV) by changing deposition conditions. The absorption data for two films, one a SiH_4 film and the other a fluorinated film, are shown in Fig. 2. As can be seen, films deposited from $(\text{SiF}_4 + \text{H}_2)$ have a higher bandgap than hydrogenated films. Whether this is due to F or O (coming from impurities in SiF_4) cannot be determined at this time. We shall do experiments to study the influence of O alone later in the program.

The flexibility in bandgap that is offered by F or O is quite important to a device designer, and can be used advantageously to increase efficiency, as will be clear from Section IV.

The fluorinated films were doped with As by including AsH_3 in the plasma. It was found that the smallest amount of AsH_3 made the films highly n-type, and highly conductive. This will be discussed in Section III.

Fig. 2

Absorption Constant of a-Si:H and a-Si:F,H

Fig. 3

Comparison of Delaware vs. RCA Samples

III. Material Characterization

The following characterization techniques have been developed to measure the material and electronic properties of the films.

<u>Technique</u>	<u>Property</u>
Absorption	Bandgap
Photoluminescence	Defect density
Infrared Absorption	Si-H bonds
Conductivity	Doping characteristics
Photoconductivity	Trap density, ($\mu\tau$) product
Thermoelectric power	Fermi level position
Field Effect	Density of states

Bandgap and infrared absorption have been described in the previous section.

1. Photoluminescence. The photoluminescence set-up was described in the report for the first quarter. We have continued photoluminescence measurements as a tool for determining film quality. We have used a good-quality RCA sample, kindly supplied to us by Dr. Jack Pankove of RCA Laboratories, as a reference sample to determine the photoluminescence efficiency of our samples. We show a side-by-side comparison of photoluminescence of our own and RCA samples in Fig. 3. As can be seen from Fig. 3, our samples have about the same efficiency as the RCA reference sample. This is only true for cathodic samples deposited from SiH_4 :He mixtures, and not for SiH_4 :Ar mixtures, where the efficiency was ~ 100 times less. This may be due to higher damage caused by heavier Ar ions in a-Si deposited from SiH_4 :Ar mixtures.

2. Conductivity. An apparatus for measuring temperature dependence of conductivity has been set up. Consequently, we can measure conductivity activation energies as a function of doping. A typical curve for $\ln\sigma$ vs. $1/T$ is shown in Fig. 4 for As-doped films. As can be seen from the curve, the activation energy for conductivity reduces significantly with As doping.

This data fits a relation of the form, $\sigma = \sigma_0 \exp(-kT/E_a)$, with $E_a = .34$ eV,

Figure 4

Conductivity Activation for n-type a-Si:H

and $\sigma_0 = 100 \text{ (ohm-cm)}^{-1}$.

A similar curve for B-doped p-type films is shown in Fig. 5.

3. Thermoelectric Power

Thermoelectric power is a very useful technique for measuring the position of Fermi level.⁽⁴⁾ We have constructed an apparatus for measuring thermoelectric power as a function of temperature to provide us with this data, and we hope to start measuring thermoelectric power during the next quarter.

4. Field Effect

Field effect is a powerful technique for the measurement of intergap defect densities.⁽⁵⁾ However, previous field-effect measurements have not been interpreted in a self-consistent manner,⁽⁶⁾ and as a result, may have given erroneous results for density of intergap states. We have performed a detailed analysis of field-effect measurement technique, and developed a computer program which analyzes data in a self-consistent manner. The major conclusions of the analysis are:

1. Field effect measurements cannot distinguish small structures in density of states unless the experimental error is less than a few percent.
2. Field-induced changes in trapped charges must be avoided for a meaningful interpretation of data.
3. The photo-induced change in dark conductivity also shows up in the field-effect curves and this indicates an apparent change in defect densities (or trap densities) with illumination.

The details of the method are in Appendix A.

Fig. 5

Conductivity Activation of p-type a-Si:H

IV. Device Design and Analysis

The work on device design has continued. We have extended the work from the previous quarter to include analysis of field-aided transport and fill factor for a-Si p-i-n devices. New structures have been designed and analyzed. The major conclusions are:

1. The device performance model, using realistic parameters, predicts $J_{sc} = 15 \text{ mA/cm}^2$, $V_{oc} = 1 \text{ V}$ and $FF = 0.72$, giving $\eta = 10.8\%$.
2. Several of the novel structures, particularly light trapping and graded bandgap junctions, can increase the efficiency by 20%.
3. There is an advantage to using lower bandgap base-layers.

The details of the analysis are included in Appendix B.

References

1. J. C. Knights, G. Lucovsky and R. J. Nemanich, J. NonCrystalline Solids, 32, 393 (1979)
2. A. Madan and S. Ovshinsky, Nature, 276, 482 (1978)
3. H. Fritzsche and C. C. Tsai, Solar Energy Materials, 1, 29 (1979)
4. G. Doehler, Phys. Rev. B19, 2083 (1979)
5. W. E. Spear, Adv. in Physics, 26, 811 (1977)
6. W. E. Spear and P. G. LeComber, J. Non-Cryst. Solids, 8-10, 727 (1972)

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Appendix B

Design Considerations for a-Si Solar Cells

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ABSTRACT

a-Si is potentially an attractive material for thin-film solar cells. However, its potential for high efficiency devices has not been realized to-date. In this paper, we examine the design considerations which can be used to develop high efficiency devices from a-Si. The design analysis takes full advantage of the flexibility in bandgap and other material properties offered by a-Si. Several structures, such as light-trapped cells, graded layer cells and tandem junction a-Si/a-Si cells are analyzed in detail for collection efficiency, V_{oc} and fill factors. It is shown that using these innovative structures, realistic conversion efficiencies exceeding 10% can be realized in a-Si in spite of the very low diffusion lengths ($\sim 0.1 \mu\text{m}$). Technological considerations for achieving such structures are also discussed.

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"Design Considerations for a-Si Solar Cells"

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I. Introduction

Amorphous Si is an interesting material for photovoltaic devices.

It has the following attractive properties:

1. It has a bandgap (1.5 - 2.0 eV) which lies in the range needed for high efficiency^(1,2)
2. It is easy to deposit
3. It has a high absorption coefficient⁽³⁾. Hence, a thin film can absorb most of the light.
4. Its electronic properties can be changed by doping with n and p type dopants.

In spite of these attractive properties, present day a-Si devices have not achieved high efficiencies. Photovoltaic conversion efficiency is limited to ~6% range. It is the purpose of this paper to explore the known material properties of a-Si and show that the reason for the poor device performance lies in poor device design, and that better device designs, based on a systematic analysis of device performance, can lead to achievement of 10% efficiency in practical devices. The paper will analyze several novel structures such as light-trapped cells, graded-gap cells and a-Si/a-Si tandem junction cells and show that some of these cells can be expected to achieve high efficiencies in spite of poor material qualities of a-Si.

II. Relevant Material Properties of a-Si

A. Bandgap. The bandgap of a-Si lies in the range 1.5 eV - 2.0 eV, depending upon the method of preparation. In general, for a-Si:H, the bandgap increases as H concentration increases.⁽⁴⁾ This can be achieved by using a lower temperature of deposition, or a higher H pressure during deposition. Similarly, doping with F during growth can change the bandgap of a-Si:F, H.^(5,6) A typical absorption curve for a-Si:F, H is shown in Fig. 1, and compared with a typical a-Si:H curve. In general, then, the bandgap of a-Si can be changed within limits by changing deposition conditions and partial pressures of gases such as H and F. This result is quite significant, because it offers the device designer a large degree of flexibility which has not been used to date. This flexibility can be used advantageously to reduce surface recombination, increase the effective diffusion length of minority carriers, make tandem cells etc.

B. Density of Intergap States. Amorphous semiconductors generally suffer from a high density of defect states in the forbidden gap between valence and conduction bands. It is well known that incorporation of H or H and F in a-Si reduces the intergap defect density by orders of magnitude.^(5,7) Defect densities may be reduced to below $10^{16}/\text{eV-cm}^3$. F, in combination with H seems to be particularly efficient at reducing intergap defect densities,⁽⁵⁾ a probable consequence of its higher bond-energy with Si.

The low densities of intergap defects are interesting to device designers for three reasons. First, the lower defect densities make doping

of a-Si relatively easy. Small levels of donors or acceptors (in the 1-1000 ppm range) can achieve relatively high conductivities [10^{-5} - $10(\Omega\text{-cm})^{-1}$], making pn junctions possible; and aiding in ohmic contact formation. Second, the relatively low defect densities allow a wide depletion layer to exist in a pn junction, thus allowing a region where there is a field-assisted minority carrier collection. This is a very significant result, because it has been found⁽⁸⁾ that free-carrier diffusion lengths in a-Si:H are relatively short ($\sim 0.1 \mu\text{m}$). Thus, a relatively wide depletion layer (~ 0.3 - $0.5 \mu\text{m}$) would increase current significantly. And finally, low defect densities imply low trap and recombination center densities, increasing lifetime of photo-generated carriers, and reducing the amount of trapped charge. The reduction in trapped charge is particularly significant, because that implies a wider depletion layer in the presence of photo-generated carriers than would be the case otherwise.

C. Electronic Properties.

- i) Conductivity. As indicated above, doped a-Si can achieve remarkably high conductivities. For n a-Si:F, $\sigma > 10(\Omega\text{-cm})^{-1}$. This fact can be useful to a device designer in minimizing series resistance, and in making ohmic contacts.
- ii) Photoconductivity. a-Si is found to be highly photoconductive, with $\sigma_p \approx 10^{-3} (\Omega\text{-cm})$ under AM1 illumination.⁽⁹⁾ This fact implies that there is a substantial minority carrier trapping effect, leading to a shrinkage in depletion layer of a junction under light; an undesirable effect. High photoconductivity also results in a reduction of series resistance of neutral base layer in a solar cell, resulting in a lower I^2R loss, which is desirable.
- iii) Minority Diffusion Lengths. It is found that a-Si:H has a very low minority carrier diffusion length ($\sim 0.1 \mu\text{m}$).⁽⁹⁾ Basically, this result

seems to arise from the fact that excited carriers in a-Si:H form excitons, which require an electric field to be split into electrons and holes.⁽⁹⁾ We do not yet know if a similar result holds in a-Si:F, H. It is also found that the free carrier mobility and lifetime in n-a-Si are much higher than in p-a-Si. This fact implies that one must use a p^+n cell, at least in a-Si:H, and not a n^+p structure.

- iv). Surface States. It is known from work of Wronski and Carlson⁽¹⁰⁾ and Williams and Crandall⁽¹¹⁾ that surface states play a very important part in determining properties of Schottky barriers on a-Si. In particular, the presence of surface states reduces the Schottky barrier height and hence open-circuit voltage V_{OC} of a-Si solar cells. The result of Williams et al where they were able to obtain a V_{OC} of 1.2 V in electrolytic a-Si cells, where surface states have been passivated, is a clear indication that practical, high efficiency a-Si devices should rely upon p^+n junction or MIS-type cells.

III. Cell Structures

A number of cell structures are possible in a-Si. In this paper, we shall basically analyze 5 such structures, and show how to increase the efficiencies in each case. The 5 structures are shown in Fig. 2.

- A. The basic cell, a simple p^+n junction, is shown in Fig. 2A. It consists of a very thin p^+ layer, an intrinsic or lightly n doped base and a back n^+ contact.
- B. Reflection enhanced cell is shown in Fig. 2B. It is basically the simple cell, but is deposited on a high reflection substrate. The substrate geometry is such that light is diffusely reflected into a-Si, and a part of light is trapped in the cell by virtue of total reflection at the front surface.
- C. Graded junction cell is shown in Fig. 2C. The p^+ junction is graded in bandgap by adjusting deposition conditions so that a built-in field exists in the junction layer.
- D. A graded-junction, graded-base cell is shown in Fig. 2D. In addition to junction grading, the base layer is graded in bandgap (or doping) so as to give a built-in field.
- E. A tandem, two-junction cell, using a high bandgap a-Si as first cell and low bandgap a-Si as second cell can also be made, and is shown in Fig. 2E.

It is, obvious that structures C, D and E can be made to have light-trapping characteristics. The influence of light trapping on C, D and E will also be studied.

IV. Basic Design Considerations.

In designing a-Si cells, the following considerations will be important.

1. Non-superposition. Since a-Si cells typically have very small diffusion lengths, a significant current collection will be from photons absorbed in the depletion layer. (see Fig. 3). As the cell comes under insolation and is under load, the cell will develop a forward voltage which will decrease the depletion layer. Hence, the current collection efficiency will decrease as light level increases, i.e. superposition principle is not valid in small diffusion length a-Si. This consideration will adversely affect both current collection efficiency and fill factor.

Another factor to worry about is trapping of holes in the base layer. A substantial hole trapping can lead to a shrinkage of depletion layer. Operationally, this can be handled quite simply by assuming that there is an effective increase in donor density in the base layer, i.e. N_D^+ is increased by a certain fraction, under light. In practice, however, for $N_D \geq 10^{16}/\text{cm}^3$, hole trapping is likely to be quite negligible, since the maximum number of holes trapped is equal to the density of mid-gap defect states. In appropriately prepared a-Si, this defect density $< 10^{16}/\text{cm}^3$. (12,13)

2. Diffusion voltage. The maximum diffusion voltage, V_D , in an a-Si p^+n junction cell is given by $E_g - (\Delta E_{fn} + \Delta E_{fp})$, where ΔE_{fn} and ΔE_{fp} are the separation of the electron and hole Fermi levels from conduction band in n type and valence band in p-type respectively. ΔE_{fn} can be very small indeed (~0.03 eV in fluorinated a-Si).⁽¹²⁾ ΔE_{fp} is somewhat larger, but can be ~0.2 eV.⁽³⁾ Thus, a V_D of ~1.3-1.4 eV for ~1.65 eV gap a-Si is a reasonable estimate to use for design purposes.

3. Surface recombination. Since a-Si can be doped quite easily, and is adaptable to bandgap tailoring, surface recombination, both at front and back surfaces, can be avoided quite easily by appropriate tailoring of doping and/or bandgaps. Hence, we shall ignore surface recombination in designing a-Si cells, i.e. $SL/D < 1$, where S = surface recombination velocity, L is effective diffusion length and D is diffusion coefficient.
4. Regional approximation. For the basic structure illustrated in Fig. 2A, we have three regions of interest (see Fig. 3).
  - (a) junction region
  - (b) depleted base region and
  - (c) neutral base region

To a very good approximation, we can say that all the carriers generated in region (b) will be collected and that carriers in region (c) only have to travel to the edge of the region (b) so as to be swept up and collected. Thus, we can use standard diffusion equations⁽¹⁴⁾ in regions (a) and (c), and count the photons absorbed in region (b), to give a total current for the device. This, or similar, regional approximation will be our basic approach for solving the problem of current collection in the a-Si cells outlined in Sec. III.

V. Collection Efficiency and Load Current of a-Si Cells

Internal collection efficiency $QE(\lambda)$, is an important parameter in solar cells. Internal collection efficiency is defined as collected carrier per transmitted photon. The behavior of internal collection efficiency as a function of wavelength of light yields valuable information on recombination in solar cells and also guides device design. The integration of

$N_{ph}(\lambda) \cdot QE(\lambda)$ over wavelength range of interest can yield the short-circuit current. Of course, one should use the relevant $QE(\lambda)$, i.e. the $QE(\lambda)$ which would exist under full illumination, in order to obtain meaningful results. (15)

In this section, we analyze the collection efficiency for the various structures outlined in Fig. 2, using the assumptions outlined in Sec. IV.

1. Simple cell

The internal collection efficiency of a simple cell is shown in Fig. 4 under two conditions: (a) short-circuit (QE_{sc}) and (b) open circuit (QE_{oc}). It is necessary to evaluate collection efficiency under both these conditions because as the diode forward potential builds up, the depletion layer shrinks, and collection efficiency drops. Thus, a diode at maximum power point, which may have a $V \sim 0.8 V_{oc}$, has a lower collection efficiency and hence J , than at short-circuit. Thus, for meaningful design improvements, we should study both QE_{oc} and QE_{sc} in materials such as a-Si where superposition does not apply.

From Fig. 4, it is obvious that for a low minority carrier diffusion length, and for a reasonable donor density, the collection efficiency in the red region drops significantly upon forward biasing of the diode. The collection efficiency drops further when the donor density increases, as shown in Fig. 5. This is expected, since a higher donor density implies a smaller depletion depth. Collection efficiency, and hence current, can be increased further if free carrier diffusion length is increased, as shown in Fig. 6. It will be seen that even for low free carrier diffusion lengths ($0.1 \mu m$), it is possible to achieve $J_{sc} \approx 14.0 \text{ mA/cm}^2$ at 100 mW/cm^2 insolation if doping and intergap defect densities can be kept low ($\sim 10^{16}/\text{cm}^3$). We

shall see in Sec. V.2 how to enhance J_{sc} , or better still J_{max} (current at maximum power point) using light trapping.

The collection efficiency decreases markedly as junction layer thickness W_1 increases, even for reasonable diffusion length L_1 in the junction layer ($\sim 300 \text{ \AA}$) as shown in Fig. 7. Hence, the necessity of keeping junction layers thin ($\sim 300\text{--}500 \text{ \AA}$),⁽¹⁶⁾ or using better designs (sec. V.3 below).

2. Reflection enhancement

As explained in Sec. III.B, reflection enhancement and partial light trapping can significantly increase currents in a-Si solar cells. It is possible to derive analytical expressions for collection efficiency under reflection and light-trapping. This is done in Appendix A. Here, we present the main results of this analysis.

While discussing reflection and light-trapping, it is worth noting that best enhancement can be achieved when the reflected photons are used most efficiently. Referring to Fig. 3, this means that the width of the base layer of the cell, $W_2 \approx W_D^{load} + L_2$, where W_D^{load} is the depletion width under load, i.e. at maximum power point, and L_2 is minority carrier diffusion length. If W_2 is much larger than $(W_D + L_2)$, photons absorbed in the "dead" region of the cell will be wasted. Thus, our simulations will be based on approximately achieving this efficient reflection-enhancement condition. Typically, $W_D \approx 0.3 \text{ }\mu\text{m}$ and $L_2 \approx 0.1 \text{ }\mu\text{m}$. Hence, $W_2 \approx 0.4 \text{ }\mu\text{m}$.

The increase in QE_{oc} achieved by using reflection and light trapping are shown in Fig. 8. The corresponding increase in J_{max} (maximum power point) is shown in Fig. 9, as a function of L_2 . Upon examining Fig. 8 and 6, it is obvious that reflection and partial light trapping are extremely important in achieving higher efficiencies in a-Si cells made from poor

diffusion length materials, and can lead to ~15% higher currents and hence, efficiencies.

3. Graded Junction Layer

As explained in Sec. II and III, it should be possible to make a graded bandgap junction in a-Si such that a built-in field is developed which would assist in electron collection and inhibit surface recombination. See fig.10. If the grading is gentle (dE_g/dx is low) and the doping is arranged so that $(E_f - E_v)$ remains relatively constant in the graded layer, then all of the field would exist in the conduction band and would provide assist to electron transport. This field would also break up the bound excitons and give rise to free carriers. It should be possible to achieve a grading of 0.2 eV over a distance of 0.1 μm , giving rise to a field of 2×10^4 V/cm. With such a large field, one expects high collection efficiency in the junction layer, and this is verified by detailed computer analysis of collection efficiency. The results of this analysis are shown in Fig.11, and are compared with the collection efficiency of a simple cell with identical junction layer thickness ($W_1 = 0.1 \mu\text{m}$) and which relies on simple diffusion transport with $L_1 = 0.1 \mu\text{m}$. The significant increase in QE at lower wavelengths leads to a predicted increase of ~13% in J_{max} . This result is very encouraging and should be a strong inducement for pursuing such gently-graded junction-layer cells.

4. Graded Base and Junction layers.

In complete analogy with subsection 3 above, it should be possible to grade the base-layer of an a-Si cell so as to create a field ($E \geq 1 \times 10^4$ V/cm) which would assist in exciton breakup and hole transport towards the junction. However, we expect intuitively that this is similar to increasing diffusion length of the base layer by a small amount (0.1 - 0.2 μm at most). Hence,

the results should be similar to the results shown in Fig. 6, and result in a few percent increase in $J_{\max}$. This is verified by a detailed computer analysis which takes account of variations in bandgap and hence absorption constant with distance. $J_{\max}$ in this case is increased ~5% over a simple cell. Note that for the field-aided transport to be effective, it must deliver its carriers approximately within a diffusion length of the depletion layer; otherwise it is useless. Thus, one must design this cell very carefully, and it may be desirable to grade the base layer starting ~0.2 μm from the edge of the junction layer.

5. Realistic Design Goals on $J_{\max}$ and J_{sc} in a-Si cells.

Based on the above analyses, realistic design goals for $J_{\max}$ and J_{sc} in a-Si cells are shown in Table I. These goals assume a very small free-carrier diffusion length in the base (0.1 μm), an effective total doping of $1 \times 10^{16}/\text{cm}^3$ in the base layer and a V_{oc} of 1 V. The current goals also assume a 10% front-surface reflection and grid-shadowing loss. It will be recognized that these assumptions are realistic and can be achieved in practice. It is seen from Table I that the strongest increase is due to reflection-enhancement, an almost 20% increase in J_{sc} for $N_D = 1 \times 10^{16}/\text{cm}^3$; reflection-enhancement gives ~16.5 mA/cm^2 . Even for large doping levels, J_{sc} of ~13.4 mA/cm^2 is realistically achievable. These results are very encouraging and may lead to achieving ~10% efficiencies (see sec. VII).

TABLE I

Expected J_{sc} and J_{max} in a-Si(100 mW/cm² insolation)

	$N_D = 1 \times 10^{16}/\text{cm}^3$		$N_D = 1 \times 10^{17}/\text{cm}^3$	
	J_{sc}	J_{max}	J_{sc}	J_{max}
Simple	13.9	12.8	11.8	10.7
Reflection Enhanced	16.5	15.0	13.4	11.9
Graded Junction	15.6	14.6	13.7	12.8
Graded Junction with Reflection enhancement	17.3	15.9	14.7	13.4

Notes: All currents in mA/cm². 10% reflection assumed: $E_g(\text{base}) = 1.65 \text{ eV}$, $L_2(\text{base}) = 0.1 \text{ } \mu\text{m}$, $(W_2(\text{base}) = 0.4 \text{ } \mu\text{m}$. $V_D = 1.4 \text{ V}$. $W_1 = L_1 = 300 \text{ } \text{\AA}$.

VI. Fill Factor in a-Si Solar Cells

A. Internal Fill Factor

As indicated above, superposition principle does not apply in a-Si, since collection from the depletion layer at the junction is a major element in collection efficiency. This, in turn, means that the internal light-generated current in a-Si solar cell drops as forward voltage builds up. In the equivalent circuit of Fig. 12, this translates into $J_L(V)$ dropping as V increases. Thus, $J_{load}(V)$ decreases due to both $J_L(V)$ decreasing with V and $j_F(V)$, the diode forward current, increasing with V . Thus, the internal fill factor, which is derived from the maximum power point for a diode with no series or shunt resistance losses, is likely to be lower than for a cell where superposition applies.

We have calculated the internal fill factor for the a-Si cells studied in Sec. V.

1. Simple Cell

The internal fill factor (FF_1) of a simple cell is shown in Table II as a function of base layer diffusion length L_2 and doping density N_D for two different V_{OC} . There are four trends indicated in Table II.

- i) As L_2 increases, FF_1 increases. This is expected, since an increase in L_2 reduces the importance of depletion layer collection
- ii) As N_D increases, FF_1 increases. This is also expected, since an increase in N_D shrinks W_D , and decreases the importance of depletion layer collection.
- iii) Reflection and light trapping serve to reduce the fill factor slightly. This is not intuitively obvious, but can be explained. As the field builds up and depletion layer shrinks, more carriers are being reflected into the diffusion region instead of depletion region, as

TABLE II

Internal Fill Factors of a-Si Cells

1) $V_{oc} = 1.0$ V

		$N_D = 1 \times 10^{16}$		$N_D = 1 \times 10^{17}$	
		No. refl.	Refl.&Lt.Trap	No Refl.	Refl.&Lt. Trap
L_2 :	.1	.831	.823	.81	.798
	.3	.837	.825	.84	.836
	.7	.851	.842	.859	.857
	1.0	.855	.849	.864	.862
	1.4	.859	.858	.867	.867

2) $V_{oc} = 0.8$ V

		$N_D = 1 \times 10^{16}/\text{cm}^3$		$N_D = 1 \times 10^{17}/\text{cm}^3$	
		No Refl.	Refl. & Lt. Trap	No Refl.	Refl. & Lt. Trap
L_2 :	0.1	.830	.820	.812	.801
	.3	.830	.818	.832	.827
	.7	.838	.829	.841	.841
	1.0	.841	.833	.847	.845
	1.4	.843	.843	.849	.849

would be the case under no forward voltage. Thus, the collection efficiency of reflected carriers is higher at short-circuit than at maximum power point, i.e. reflection makes more impact on J_{sc} than on J_{max} . Hence, FF_1 decreases slightly in reflection enhanced cells as compared with simple cells.

iv) As in other, more familiar cells, FF_1 reduces as V_{oc} decreases.

The major point to note from Table II is that internal fill factors are quite high, ~0.8 or greater, even for low V_{oc} (0.8 V). Hence, obtaining good external fill factors (fill factors in the presence of series and shunt resistance) should be possible. We address this factor next.

B. External Fill Factor

External fill factor, FF , is reduced from internal fill factor, FF_1 , due to two reasons: series and shunt resistances. Shunt resistance is an externality not directly related to device design. Series resistance, on the other hand, is intimately related to device design. Two components of series resistance are important in a-Si cells:

1. Base layer resistance. The resistance of the undepleted base layer introduces an undesirable power loss. The fractional fill factor loss is approximately given by the fractional power loss. The fractional power loss due to a series resistance R_s ($\Omega\text{-cm}^2$) is given by:⁽¹⁷⁾

$$\% P_{loss} = 100 \cdot \frac{J^2 R_s}{P_{gen}} \quad (1)$$

where P_{gen} is power generated per unit area and J is the current density.

For a-Si base layer, $R_s \approx \rho W_2$, under illumination,
 $\rho \approx 5 \times 10^{+3} \Omega\text{-cm}$ or less;⁽⁹⁾ W_2 is $< 0.5 \mu\text{m}$ for low diffusion

lengths. Hence, $\% P_{\text{loss}} < 0.5\%$ for 10% efficiency cell, an entirely negligible fraction.

2. Junction Sheet Resistance.

Junction sheet resistance may present severe problems in a-Si. This is because p^+ layer is very thin ($\sim 300\text{--}500 \text{ \AA}$) and the resistivity of the layer is quite high ($\sim 10^2 \Omega\text{-cm}$ or higher). Thus the sheet resistance, $R_{\square}$, may be $3 \times 10^7 \Omega/\square$. This is a very high $R_{\square}$. The fractional power loss due to sheet resistance is given by: ⁽¹⁸⁾

$$\%P_{\text{loss}} = 100 \cdot \frac{R_{\square} J^2 s^2}{12 P_{\text{gen}}}$$

where s = spacing between grids

For $\%$ loss to be $\sim 5\%$, $s \approx 9 \mu\text{m}$.

For 5% light loss, grid thickness (W_g) would have to be $0.5 \mu\text{m}$, an unrealistic value for large area cells. Hence, we must reduce the sheet resistance of the a-Si junction by suitable techniques. Two techniques are possible.

- (1) Use of a conducting, transparent oxide such as Indium-Tin oxide or Tin oxide, ⁽¹⁹⁾ on the junction layer. Conductings, heavily doped oxides can have transmission of $\sim 90\%$ and sheet resistance of $< 10^3 \Omega/\square$. Such a $R_{\square}$ would increase $s \approx 1.2 \text{ mm}$, with 2.5% power loss. This allows the grid width to be $\approx 75 \mu\text{m}$, an easily achieved width. Typically, $R_{\square}$ is even lower ($\sim 100\text{--}300 \Omega/\square$), allowing $s \approx 2 \text{ mm}$ and $w_g \approx 100\text{--}125 \mu\text{m}$, which can be achieved by screen printing.
- (2) Use of a thin metal layer. A thin ($50 \text{ \AA}$) high transparency metal layer (gold, Mo etc.) would also reduce $R_{\square}$ significantly and yet absorb $\sim 10\%$ of photons $R_{\square}$ of $\sim 50\text{--}100 \Omega/\square$ can easily be achieved under such conditions, allowing wide grid spacings.

C. Realistic Goals on FF

Based on subsections A and B above, a realistic goal for FF in practical a-Si solar cells is $FF = 0.75$ or better, even for rather poor diffusion lengths and high dopings. Under favorable conditions, FF of .78 is not unreasonable to expect. Significant power leakage via shunts will, of course, reduce these levels, usually by <5%. Thus, a FF of 0.72 is a very conservative design goal which seems likely to be met in practice.

VII. Realistic Efficiency Goals.

A. Standard Cells.

Based on the discussions in the preceding sections, realistic design goals on the efficiency of the different a-Si cells are shown in Table III. These assume of V_{oc} of 1.0 V, a bandgap of 1.65 eV and FF of 0.72. As before, a 10% front-surface reflection loss is assumed.

It is observed from Table III that there are a number of ways of achieving high efficiencies in a-Si (~10%). The most interesting design seems to be reflection-enhancement, coupled with graded gap junctions. This design can be further improved by optimizing the grading of the bandgap and the thickness of the graded layer. However, these optimizations will have to await more detailed measurements of material properties expected in such graded layers.

The numbers in Table III are representative values for a typical $E_g \sim 1.65$ eV. Changing the gap, of course, can lead to other values of η . The efficiency of a simple cell as a function of bandgap of a-Si is shown in Fig. 13. It is assumed that as E_g increases, V_{oc}

TABLE III

Realistic Design Goals for a-Si Cells

(100 mW/cm² insolation)

$$N_D = 1 \times 10^{16}/\text{cm}^3$$

$$N_D = 1 \times 10^{17}/\text{cm}^3$$

	Simple	RE	Graded junction	RE & Grad. Junction	Simple	RE	Graded Junction	RE & Graded Junction
J_{sc} (mA/cm ²)	14.0	16.5	15.6	17.3	12.0	13.0	13.6	14.6
$\eta\%$	10.0	11.8	11.2	12.4	8.6	9.6	9.8	10.5

Assumptions: (i) $V_{oc} = 1.0$ V

(ii) FF = .72

(iii) 10% front-surface reflection loss.

increases. A representative V_{oc} of $0.61 \cdot E_g$ (which would give a 1V V_{oc} for 1.65 eV material) is used for these calculations.

We note from Fig. 13 that as E_g decreases, η increases. This result is not surprising, since we are on the high energy side of the Loferski curve,⁽¹⁾ where η is expected to increase with decreasing E_g . An additional reason for increasing η is that as E_g decreases, a greater proportion of photons is absorbed in the depletion layer. Hence, proportionately, current increases faster than V decreases.

Fig. 13 is only meant to be representative of the trend of results. The actual efficiency for any given bandgap, of course, will depend upon material properties for that E_g . The material properties are very sensitive to preparation conditions. Thus, the choice of optimum E_g for a-Si cells will have to await a detailed determination of material properties of a-Si for different bandgaps.

VIII. Two Junction a-Si/a-Si Cells.

As we have seen, the bandgap of a-Si can be changed rather easily by changing deposition conditions. The variation in bandgap from 1.5 - 1.9 eV offers the possibility of designing a tandem junction a-Si/a-Si solar cell (Fig. 2E) where the first cell has a high bandgap and the second one a low gap. Such a combination would increase the efficiency of the cell, because the photon spectrum could be used more efficiently. (20)

The efficiency of a two-cell structure, connected by a thin $n^+ - p^+$ tunnel diode, is shown in Table IV for a simple cell. We again assume a 10% reflection loss, $V_{oc} = .61 * E_g$, $V_D = E_g - 0.25$ eV and $N_D = 1 \times 10^{16}/\text{cm}^3$. The optimized efficiency of a two-cell system is arrived at by selecting bandgaps (E_g^A , E_g^B), which match J_{max} in the first and the second cell for different combinations of (W_2^A, L_2^A) , (W_2^B, L_2^B) . (The superscripts A and B refer to first cell and second cell respectively). The detailed design procedures for tandem, thin-film cells will be published elsewhere. Here, we present the representative results.

It can be seen from Table IV that a tandem-cell system is attractive if E_g^A and E_g^B can be widely separated. A reflection-enhanced tandem cell has a 11% efficiency advantage over a single gap reflection-enhanced cell. However, the inherent losses (e.g. voltage loss at tunnel junctions, non-matching of currents when insolation spectrum changes etc.) will cause at least a 10% performance loss from that predicted in Table IV. This is why a tandem a-Si/a-Si cell is not all that attractive from a practical viewpoint. A wider separation of E_g^A and E_g^B , which can serve to enhance the currents, would be far more attractive. Such a wider separation can be achieved by using a-(Si, Ge) alloys. (21) A detailed simulation of such a system will be published later.

TABLE IV

Efficiency of Tandem a-Si/a-Si Cells.

1. Cell Parameters

	$N_D = 1 \times 10^{16}/\text{cm}^3$		$1 \times 10^{17}/\text{cm}^3$	
	Simple	Reflection Enhanced	Simple	Reflection Enhanced
$E_g^A (\text{eV})$	1.90	1.90	1.9	1.9
$E_g^B (\text{eV})$	1.50	1.58	1.5	1.54
$W_2^A (\mu\text{m})$	0.3	0.3	0.2	0.2
$W_2^B (\mu\text{m})$	0.4	0.4	0.4	0.4

2. Cell Performance

	Simple	Reflection Enhanced	Simple	Reflection Enhanced
$J_{sc} (\text{mA}/\text{cm}^2)$	8.3	8.6	6.9	7.0
$V_{oc}^A (\text{V})$	1.16	1.16	1.16	1.16
$V_{oc}^B (\text{V})$	0.92	.96	.92	.94
$V_{oc}^T (\text{V})$	2.08	2.12	2.08	2.10
$\eta\%$	12.4	13.1	10.3	10.6

CONCLUSIONS

In this paper, we have examined the design considerations for a-Si solar cells. A number of technologically useful device designs have been evolved and their performance analyzed, using realistic and achievable material properties. The remarkable flexibility in the bandgap and material properties of a-Si which is achieved by changing deposition conditions, H and F ratios and concentrations of dopants such as AsH_3 and B_2H_6 , has been used to full advantage in designing optimized devices. Innovative designs such as reflection-enhanced cells and bandgap-tailored cells offer the realistic possibility of achieving $\eta \approx 12\%$ even for very small diffusion lengths ($0.1 \mu\text{m}$). The achievement of such high efficiencies in a-Si would depend greatly on a thorough study of the material properties of a-Si under a variety of conditions. It is fair to say that the knowledge of a-Si materials is in the infancy right now, and that intense and systematic work over the next few years will lead to a more thorough knowledge of a-Si, which in turn will allow the full photovoltaic potential of a-Si to be realized.

Appendix A

Analysis of Reflection Enhancement.

Let the reflection coefficient at back surface be R_2 and internal reflection coefficient at front surface be R_1 (see Fig. 14).

Consider first the forward travel of light (front-wall cell). Let the partial collection efficiencies at wavelength λ of the three regions of Fig. 3 (junction, depletion and diffusion) be denoted by $Q_1(\lambda)$, $Q_2(\lambda)$ and $Q_3(\lambda)$ for forward light passes. (The partial collection efficiency for any region is defined as the ratio of carriers collected in that region to the total photon flux transmitted into the cell). Similarly, let the partial collection efficiencies during a reflected (back-wall cell) light pass be denoted by $Q_4(\lambda)$, $Q_5(\lambda)$ and $Q_6(\lambda)$. The partial efficiencies for junction and diffusion region (Q_1 , Q_4) and (Q_3 , Q_6) are given by using the equations derived by Rothwarf et al;⁽¹⁴⁾ and

$$Q_2(\lambda) = e^{-\alpha W_1} (1 - e^{-\alpha W_d}) \quad (1)$$

$$Q_5(\lambda) = e^{-\alpha W_2} (1 - e^{-\alpha W_d}) \quad (2)$$

then, it is easy to show from simple algebra that the total quantum efficiency under reflection, $QE(R_1, R_2, \lambda)$; is given by:

$$QE(R_1, R_2, \lambda) = \frac{1}{1 - R_1 R_2 \exp(-2\alpha W)} [Q_1(\lambda) + Q_2(\lambda) + Q_3(\lambda) + R_2 \exp(-\alpha W) \{Q_4(\lambda) + Q_5(\lambda) + Q_6(\lambda)\}] \quad (3)$$

$$\text{where } W = W_1 + W_D + W_2$$

The current is obtained by integrating over wavelength,

$$J = \int_{\lambda_1}^{\lambda_2} QE(R_1, R_2, \lambda) N_{ph}(\lambda) d\lambda$$

where $N_{ph}(\lambda)$ is the photon flux at λ , $\lambda_1 \sim 0.35 \mu m$ for AM1 solar spectrum

and λ_2 is the wavelength where absorption becomes very low (e.g. $\alpha < 1 \times 10^3 \text{ cm}^{-1}$).

References

1. J. Loferski, Proc. IEEE, 51, 677 (1977).
2. D.E. Carlson and C. Wronski, J. Electron Mater. 6, 95 (1977).
3. W. Spear, Adv. in Physics, 26, 811 (1977).
4. D.E. Carlson et al. "Amorphous Si Solar Cells," Final Report 1978 (RCA Laboratories, Princeton, NJ).
5. A. Madan, S.R. Ovshinsky and E. Benn, Phil. Mag. (to be published, 1979).
6. V.L. Dalal, F. Alvarez and C.M. Fortmann, to be published.
7. A. Madan, P.G. LeComber and W.E. Spear, J. Noncryst. Solids 11, 219 (1976).
8. C. Wronski, IEEE Trans. Electron Devices, ED-24, 351 (1977).
9. R. Crandall and R. Williams, J. Appl. Phys., July 1979 (to be published).
10. C.R. Wronski and D.E. Carlson, Solid State Comm. (1977).
11. R. Williams and R. Crandall, J. Appl. Phys. (to be published, August 1979).
12. S.R. Ovshinsky and A. Madan, Nature 276, 482 (1978).
13. I. Balberg, Phys. Rev. 43 48 (1979).
14. A. Rothwarf, L.C. Burton, H.C. Hadley and G.M. Storti, Proc. 11th IEEE Photovoltaic Conf., p. 476 (1975).
15. V.L. Dalal and A. Rothwarf, J. Appl. Phys. 50, 2980 (1979).
16. B.T. Debney, Solid-State and Electron Devices 2, 515 (1978).
17. V.L. Dalal, Proc. 13th IEEE Photovoltaic Conf. (Washington, 1978).
18. N.C. Wyeth, Solid State Electron. 20, 629 (1977).
19. J.L. Vossen, in "Transparent Conducting Films," Physics of Thin Films 2, 1-71 (1977) (Academic Press, New York).
20. J. Loferski, Proc. 12th IEEE Photovoltaic Conf. (Baton Rouge, LA) p. 957 (1976).
21. J. Chevallier, H. Wieder, A. Onton and C.R. Guarnieri, Solid-State Comm. 24 867 (1978).

Figure Captions

1. Absorption coefficient for a-Si:H and a-Si:H,F (ref. 6).
2. Solar cell structures analyzed in this paper.
3. Regional approximation for a-Si solar cells.
4. Calculated spectral response curve for a-Si:H p^+n cell with $E_g = 1.65$ eV. p^+ layer is 300 Å thick, $L_1 = 300$ Å, n layer is 0.4 μm thick and diffusion length in n layer is 0.1 μm. $N_D = 1 \times 10^{16}$ cm⁻³. $V_{oc} = 1$ V. QE_{sc} denotes collection efficiency at short-circuit, and QE_{oc} , internal collection efficiency at V_{oc} .
5. Collection efficiency as a function of effective (doping and defect) density N_D . Other parameters as in Fig. 4.
6. Variation of J_{sc} and J_{max} (maximum power point) with minority diffusion length.
7. Variation of collection efficiency with junction layer width W_1 . $L_1 = 300$ Å is assumed.
8. Influence of back-surface reflection and partial light trapping on QE_{oc} . $R_2 = 85\%$ and $R_1 = 50\%$. Other conditions as in Fig. 4.
9. Influence of partial light trapping and back reflection on current at maximum power point.
10. Band diagram of a graded junction-layer cell.
11. Collection efficiency of a graded layer cell.
12. Equivalent circuit of a solar cell.
13. Efficiency of a simple cell as a function of bandgap. $V_{oc} = 0.61 \cdot E_g$. $N_D = 1 \times 10^{16}$ /cm³. Other parameters as in Fig. 4.
14. Reflection coefficients R_1 and R_2 .

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Fig. 1

A. Simple Cell

B. Reflection & Partial Light Trapping

C. Graded Junction Cell

D. Graded Junction & Base Cell

E. Tandem Junction
a-Si/a-Si Cell

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