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UNITED NATIONS
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STUDY ON AMORPHOUS SILICON SOLAR CELLS*

prepared by

Arun Madan **

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1.0 Introduction

This article reviews the potential of the Amorphous Silicon (a-Si) for use in inexpensive solar cells applications. This article is meant as a generalized backgound material, whilst fuller technical details can be found in Appendix B, where a chapter entitled "Amorphous Silicon Solar Cells" by A. Madan, Eds: C.P. Khattak and K.V. Ravi. Pubs: North Holland (1985), is included for reference.

A solar cell is a device designed to convert sunlight directly into electrical power. It is attractive from an energy point of view as it represents a potentially inexhaustible source of energy, unlike depletable resources such as coal, gas and oil. Solar cells were originally designed for the space program and were constructed from high quality single crystal Si materials. It is by far the most intensively studied and has attained a photovoltaic conversion efficiencly in excess of 20% under AM-1 (Air Mass) condition. To date, crystalline Silicon has been the most widely used technology expecially in stand alone applications. Figure 1 shows the basic steps involved in the fabrication process. There are two points worth emphasizing: (1) the temperatures involved in the fabrication process are quite high, in excess of 1000°C and hence it is an extremely energy intensive process, (2) during the cutting process, in excess of 50% of the material is lost since the blade width is

on the order of the thickness of the wafer. It is for these reasons, that further large scale terrestrial usage is not envisaged since it appears that this technology may not be able to meet the stringent cost goals (< $1/pW) which is required to compete with other forms of energy production. Hence two types of approaches are now under consideration: flat plate and concentrator systems. In the former, the major factors affecting the perfomance criteria are the support structures, the cost of land, material costs and availability. The primary material under consideration, at present, is Amorphous Silicon based alloy. In the latter approach, the primary cost factors to consider are the tracking mechanisms and concentrators involving lenses and cooling systems; the material under consideration is crystalline GaAs, where the goals are to reach 35% conversion efficiency. The inclusion of a tracking mechanism introduces a disadvantage, as moving parts are now introduced into the total photovoltaic system.

In Table 1, we summarize the more important solar cell technologies, with their advantages and disadvantages noted, as well as the production volumes reported by various companies. Fig. 2 shows the total module PV shipment in 1985, as reported by the U.S. Department of Energy (DOE), and note that, a-Si has captured 32% of the total worldwide market. It is envisaged that in 1986, a-Si may approach 50% of the worldwide market. The potential for solar cells is immense and as the $/pW for the cost of production continues to decrease, various market

segments open up. In Table 2, we show a possible scenario for the deployment of solar cells with major growth area identified to be in the developing contries with the applications primarily aimed at village electrification, etc. In order to address these lucrative markets the actual cost of production needs to be decreased. For this, a-Si is now the major contender and in Table 3 we compare qualitatively, the properties of amorphous and crystalline Si. It should be noted that the advantages for the a-Si are much lower material utilization and the ability to fabricate complete monolithic panels. We shall discuss these aspects in more detail below.

There has been an intense research and development activity in the last decade into the opto-electronic properties of a-Si and has culminated in commercial activity in a wide range of important applications. There are many companies actively selling small and large area solar panels (Arco Solar, Sanyo, Fuji, Kyocera, Savonics, Solarex, Chronar etc.), electrophotography drums (Canon, Kyocera), detectors (Sanyo, ECD), compact scanners (Fuji, Xerox) and amorphous silicon manufacturing equipment (GSI, Anelva, Ullvac, etc.). In the development stage are the thin film transistors (TFTs) for displays (Sanyo, Toshiba, Hoseiden, Ovonic Display Systems). The technological importance of a-Si, particularly the hydrogenated variety (a-Si:H), owes it origins to the pioneering work of researchers, in Britain (Standard Telephone Lab. and the University of Dundee) in the early 1970s. Because

of the highly photoconductive nature of this material, it initially prompted a use in solar cells. The success in this application has led to a-Si photovoltaics capturing 32% of the 25 MW shipments in 1985, as shown in Fig. 2. The fundamental and the applied work in this area has spawned a whole host of applications and products and many companies,particularly in the U.S. and Japan, are now in the process of exploiting this important and versatile material.

In this article, we shall consider what makes a-Si so attractive for a wide variety of applications, and in particular discuss its use for solar cells.

2.0 Some aspects of Amorphous Silicon Materials and Devices

A periodic material such as crystalline Si exhibits a forbidden gap which leads to the semiconducting behavior. The inherent disorder present in the amorphous semiconductor, (as discussed in Appendix A) leads to the concept of a mobility gap. The inherent disorder creates a tail of localized state emanating from the conduction and valence band such that at a particular energy (E_c and E_v, shown in Fig. 3), the mobility of the carriers (electrons and holes) changes by orders of magnitude. E_c and E_v are referred to as the mobility edge and the energetic region between E_c and E_v, is known as the mobility gap and is the amorphous semiconductor counterpart to the forbidden gap found in crystalline semiconductors. The

presence of these localized states, or defect centers, affects the materials and consequently the device performance.

Amorphous Silicon films have been prepared using numerous deposition techniques, such as glow discharge (Plasma Enhanced Chemical Vapor Deposition), reactive sputtering, CVD, reactive evaporation etc. Although, it had been demonstrated that in principle a continuous random network of a-Si (devoid of dangling bonds or traps) could be produced, nevertheless, results of evaporated Si or sputtered Si films revealed that the density of localized states (DOS) in the gap was far too high to be of any use in any device application. It was the accidental discovery by the researchers at the University of Dundee which revealed that the glow discharge (GD), or PECVD, a-Si prepared from SiH_4 possessed a very low DOS. It was subsequently discovered that these types of films contained approximately 10 atomic percent Hydrogen and hence are appropriately referred to as a Si:H type alloys. The low DOS of these types of materials is attributed, in part, to the satiation of the dangling bonds by H.

The GD, or the PECVD, technique is now the most important deposition method. In its simplest form, SiH_4 (Silane) gas, is passed at a controlled rate between two electrode plates (one grounded and the other excited by an electric field). The field creates a plasma which decomposes SiH_4 into its constituents and the Silicon deposits on to a substrate

situated in the plasma region. Figure 4 shows a GSI state of the art, multichamber PECVD system with the Silane plasma clearly visible. However, the key in obtaining "device quality" material is controlled by many deposition parameters such as pressure of the process gas, its flow rate, substrate temperature, power dissipation, excitation frequency, system geometry. It is found that good materials are generally prepared from low power and high flow rate conditions such that the SiH_4 gas does not deplete too much. In Table 4(a), we outline some of the conditions that are required for a-Si:H layer deposition. The low DOS in a-Si:H material results in desireable properties as far as the devices are concerned, such as relatively long minority carrier diffusion length, and the ability to dope it n-type and p-type (achieved by the introduction of PH_3 and B_2H_6 in the gas phase, respectively). Some of the opto-electronic properties of the material are summarized in Table 4(b).

As mentioned in the Appendix A, a-Si:H alloys exhibits low carrier mobilities and consequently results in a relatively small minority carrier diffusion length (0.5 - 1.5 μm). This is to be contrasted with large mobilities (> $500cm^2s^{-1}V^{-1}$) and long diffusion lengths found in crystalline Si. However a-Si:H exhibits a direct band gap which has a beneficial aspect for solar cells since very thin films can be utilized whose thickness is on the order of the minority carrier diffusion length; hence high conversion efficiencies are possible and

achieved. Another major factor for the interest in a-Si:H
material is that there is no size limitations to its deposition
area; in contrast, the crystalline Si is generally prepared in
a wafer form whose diameter is only about 5 inches. Because
of the low mobilities of the carriers and no size limitation,
then a-Si:H is generally considered for any large area
applications where high speeds of operations are not of
paramount importance such as solar cells, large area displays,
electrophotography, imaging, etc.

When light is incident on a solar cell, electron-hole pairs are
created whose extraction from within the device leads to the
current-voltage (I-V) characteristics which passes through the
fourth quadrant, as shown in Fig. 5. The actual operating
point on the I-V curve is determined by the load resistor whose
value should be such that the device is biassed at the maximum
power point, defined as the fill factor, FF. The conversion
efficiency of a cell is defined by the product of the short
circuit current density (J_{sc}), the open circuit voltage (V_{oc}),
and the the fill factor (FF) divided by the input power. A
rule of thumb is that on a clear day, the intensity of the sun
at the earth's surface is approximately 100 watts per square
foot, so that a panel rated with 10% conversion efficiency
translates to approximately 10 watts per sq. ft. of illuminated
area.

The conversion efficiency, η, of a practical solar cell is

limited by intrinsic and extrinsic losses. The latter include
losses due to reflection and series resistance of contacts.
The former includes incomplete extraction of the photogenerated
carriers and is primarily due to the photogenerated electron-
hole pairs recombining via defect centers present within the
device. This process is known as non-radiative recombination
process. The intrinsic loss also includes the inability of a
cell with a specific optical band gap, E_g, to properly match
the broad solar spectrum. Therefore, photons with energies
less than E_g, are not absorbed by the material whilst those
with energies in excess of E_g, lose their extra energy as heat.
Further fundamental losses occur because of recombination
mechanism which puts an upper limit to the V_{oc}. For
crystalline materials, such as Si, the predominant
recombination mechanism is band to band. For small and large
band gaps the conversion efficiency by necessity must be small
and detailed calculations show that η exhibits a broad maximum
between 1 and 2 eV with the consequence that many
semiconductors become viable contenders for solar cell
applications.

The situation is less clear for amorphous semiconductors.
Because of the presence of localized states within the mobility
gap, an upper limit to the V_{oc} and FF occurs due to non-
radiative recombination. Therefore, in principle, a maximum in
efficiency can occur at any E_g and is dependent on the details
of the DOS and their associated capture cross section areas.

There have been many attempts made to derive the conversion efficiency of a-Si:H solar cells with estimates differing by a factor of three. The major difficulty in deriving these estimates lies in formulating the exact mechanism of carrier transport in the devices. The primary difference between the a-Si:H alloy and the crystalline material is that the former possesses a non-uniform DOS composed of inherent band tails (defects) and deep defect states due to either processing or impurities. All of these defects provide a mechanism such that the photogenerated electron-hole pairs can recombine; hence, these defects constitute a major loss mechanism within the device. As yet, the exact DOS spectra is not known and more importantly, little is known about the capture cross sectional areas associated with the defects. This presents a major problem in determining the exact recombination mechanism. In deriving the estimate to the conversion efficiency, what is assumed is that there is a parentage associated with these states such that the states emenating from conduction and valence bands are acceptor and donor types respectively; this parentage is also lumped, incorrectly, with the deep defect states some of which are associated with impurities. Using this, as well as a reasonable assumption to the DOS spectra, one calculates under steady state illumination conditions , the equilibrium concentration of free carriers from which the quasi Fermi levels can be determined, whose separation determines the V_{oc}. In this way, the maximum of V_{oc} is determined to be 0.9 - 1.0 V which can be improved to about 1.2V if the band tails can

be made sharper which is entirely possible with better
processing techniques; this can lead to an improvement in
conversion efficiency of about 30% and would constitute a major
breakthrough. The short circuit current density is trivial to
calculate from the knowledge of the absorption coefficient and
the known global AM 1.5 solar spectrum. By assuming a quantum
efficiency of unity for total int--- absoprtion, the maximum
to J_{sc} is about $21mAcm^{-2}$. Fill factor is the trickiest to
calculate and involves the solution of the continuity equations
and is reliant on the knowledge of the recombination
mechanisms. In the absence of this, at best, device modelling
leads to a crude estimate. In its simplest form, FF depends on
how the total collection width varies with the bias voltage.
To a first approximation the collection width is a sum of the
depletion width and the minority carrier diffusion length. For
diffusion lengths on the order of the thickness of the cell (~
6000-8000Å), FF have been estimated to be about 0.8. Therefore
the upper limit to the conversion efficiency of a single
junction cell is about 18% and shown in Table 5.

A solar cell requires a built in electric field (rectifying
junction) such that the electron-hole pairs created by the
incident illumination can be separated and collected by the
external contacts. In crystalline Si, the field is created at
the juncture of the p^+ and n^+ layers. Since p^+ and n^+ layers
in a-Si:H based materials are highly defective, a significant
rectifying junction is not possible. Instead, an intrinsic

layer is inserted between the p^+ and n^+ layers with the field occuring at the p^+/i and the n^+/i junctures. The normal structure of an a-Si:H p^+-i-n^+ solar cell is shown in Fig. 6. Wide band gap p^+-layer of about 100A in thickness is deposited onto a textured, transparent conducting oxide (TCO) film, followed by 5000 - 7000A thick i-layer deposition. Next a thin (100A) n^+-layer is deposited and the cell structure completed with a metal reflector, such as Al or Ag. The use of textured transparent conducting oxide (TCO) substrate and reflector maximizes the light trapping effect in this type of thin solar cell. Use of these optimized structures, several groups, notably the Japanese (Sanyo and Fuji), have reported efficiencies in excess of 11%.

One approach that would significantly improve the conversion efficiency is the use of a multijunction or tandem cell techniques. In this the cells are connected in series and stacked on top of each other, in the configuration, $p^+i_1n^+pi_2n^+$, with the wider band gap material (i_1) facing the incident illumination. In this type of arrangement, the low energy photons are directed to cells fabricated from materials with narrow band gaps (i_2) and the high energy photons are directed to wide band gap cells (i_1). The low energy photons pass through the cells until they reach a cell which can convert them to useful power. The thicknesses and the values of the band gaps of the different semiconductors are arranged such that the current generated from the constituent cells are

the same.

Since by far the most useful amorphous material for solar cell applications is presently the a-Si:H alloy with a band gap of 1.7 eV, then at present we are restricted to form multijunction stack cells based around this semiconductor. Therefore, a major focus of research is the synthesis of new types of amorphous semiconductors. In general, the addition of Ge or Sn to the a-Si:H alloy lowers the band gap primarily because the stronger Si-Si bonds are replaced by the weaker Si-Ge or Si-Sn bonds. In contrast the inclusion of N or C leads to larger band gaps. In principle, alloying (with Ge, Sn, C or N) will introduce compositional disorder in addition to the positional disorder inherent in a-Si:H films. The effect of this would be to make the conduction and valence band tails shallower still. Also, it is generally found that extra deep localized states are also introduced by alloying. These effects result in an increased recombination traffic of the photogenerated carriers. In addition it has been pointed out that the quest for a low defect states in the mid gap region is perhaps insufficient and that attention should also be paid to the extent and width of the band tails, if the alloying techniques are to succeed. In Table 5, we show the conversion efficiencies which are probable if new semiconductors with tails as sharp as a-Si:H can be obtained. Using the tandem cell approach, conversion efficiency in excess of 12% have been reported (Osaka University, ECD) and there are distinct possibilities that

conversion efficiencies of about 18% are attainable within the next 3 years.

Stability is an issue which confronts the commercialization of solar cells for large scale power applications, such as utilities. The energy payback period is related to the cost and the total power delivered by the panels. The quoted required figure is usually 20 years although it could be much less if the panels are inexpensive. Degradation has been observed in a-Si:H solar cells and is a function of the operating conditions; it is greatest at V_{oc}, reduced at J_{sc} and is virtually elimiated under reverse bias conditions. The degradation has been linked to the so called Staebler-Wronski (SW) effect and it appears that it is caused by the recombination of excess carriers whose origin may not be important. Also, some of the degradation phenomena has been linked to oxygen impurity within the device and the inherent stress of the film which in turn can break some of the weak Si-Si bonds. Also, it has been noted that after degradation the device can be restored to its original performance upon annealing at temperatures of about $150^{\circ}C$ for a few minutes. Since the operating temperature of a panel in the field will be about $50-80^{\circ}C$, then to a certain extent this effect is self healing.

Despite these problems the degradation can be device engineered out. The degradation appears to be self limiting in the sense

that the number of dangling bonds created saturates which in turn means that the collection width decreases and eventually saturates to a smaller value. Therefore if the device thickness is approximately equal to the smallest collection width attained, then the device should exhibit stability and the problem of degradation is circumvented. Of course, the overall efficiency would be lower if we restrict ourselves to a device consisting of a single juction fabricated from a thin intrinsic layer. The overall efficiency is recovered by a vertically stacked junction and thereby also avoiding the degradation. These types of structures are reported to show a degradation of less than 10% over a projected 20 year lifetime.

3.0 Mass Production Processes

Amorphous Silicon has the potential of becoming a practical source of electrical power since the fabrication techniques are suitable for large area and that a variety of substrates such as glass, ceramics, stainless steel and metallized plastics can be used. In order for the technology to become practical, several criteria must be met. Most importantly, an adequate conversion efficiency must be attained and should be about 10% over large areas. Currently, large area efficiencies are in the range 4-8%. Further, the cell performance characteristics achieved in small laboratory scale cells must be successfully scaled to large areas. Finally, practical solar cell structures must be utilized and low cost fabrication processes

implemented. A major advantage of a-Si:H material is that series connected cells, as shown in Fig. 6, covering large areas can be manufactured in a monolithic fashion. The use of this design is one of the factors that can bring the cost of the panels down. The most preferred way is by the use of a glass substrate on which a TCO is deposited. This is followed by the deposition of a-Si:H single or tandem junction and finished off with a metal contact. The cells are scribed at appropriate places to effect a series connected array. The choice of the substrate, whether it is glass, stainless steel, plastic or ceramic is an issue. It would appear that glass has advantages over the other types of substrates. Firstly, since glass is an insulator a monolithic panel can be constructed with ease, as shown in Fig. 6 (Fig. 7 shows the picture of a large area Arco Solar module rated at about 6% efficiency), which is not the case on a more expensive substrate such as stainless steel where the stainless steel acting as a common electrode prevents series connection of panels. This, of course, can be circumvented by depositing a cell over large area which is then subsequently cut and physically interconnected. This procedure increases the cost of panel production and ignores the enormous advantage of the a-Si based technology.

The fabrication of a complete photovoltaic panel requires a multistep process and the integration of many well known technologies. The final cost of a panel will ultimately depend

on cost reduction at every stage. An emphasis has been placed
recently by many researchers on higher deposition rates for the
i-layer. However, attention only to this wnile excluding other
more important steps will not significantly decrease the cost
of panels. Some of the key factors are (1) the improvement in
the quality of the TCO in terms of its sheet resistivity,
transmission and texture, (2) novel scribing steps need to be
implemented since the conventional approach using lasers, apart
from causing some damage to the cell, is slow and can be one of
the rate limiting steps in production, (3) further improvements
in yield are required and can be traced to pin hole formation
and is due to either process conditions in terms of gas phase
nucleation or the dust inclusion from the ambient.

The design of the panel requires consideration of optical and
elctrical loss. The major electrical loss (I^2R) is incurred in
the TCO layer whilst the optical losses are related to the loss
of transmission due to the TCO and the area losses caused by
the patterning process. Detailed considerations show that an
efficeint design of a panel can lead to a total loss of only
15%. In the following, we briefly summarize some of the
criteria required for mass production plant. This would
require a complete integration of the following technologies:
TCO, a-Si p-i-n, scribing and metallization. In the following,
we consider two of the more important aspects, TCO and a-Si
depositions.

3.1   TCO Requirement

Indium-Tin-Oxide layers are ruled out since it is well known
that Indium diffuses into a-Si:H alloy.   It is more appropriate
to use SnO_2:F with the basic requirement that $R\Omega/_\square < 10$ with
transmission exceeding 80% over the visible portion of the
solar spectrum.   Further with the appropriate degree of
texture, then efficient light trapping within the cell can be
attained and hence can lead to large short circuit current
densities within the solar cell.   Texture is one of the major
factors in obtaining high efficiency devices.

3.2   A-Si p-i-n Junction Fabrication Approaches

3.2.1   Batch Type System

a-Si p-i-n junctions can be produced in a batch type systems
where the three semiconducting layers are produced in the same
system one after another.   This has several major
disadvantages. (a) This is a slow process since it requires
loading, pump down, heat up, deposition, cool down and unload.
The impurity levels such as O, C and H_2O vapor are relatively
high and when included into the films leads to a deterioration
of the opto-electronic properties of the material and
consequently to a degradation in the device and hence panel
performance.   In fact, there is evidence in the open literature
that some of the degradation phenomena associated with device

performance is related to O and C contamination. In the
sequential deposition of the p-, i-, and n- layers, by
necessity there is a cross contamination of Boron from the p-
layer which is then included into the intrinsic layer. This
leads to a reduction in the $\mu\tau$ products of the hole transport
(μ is the mobility, τ is the recombination lifetime); this
leads to a reduction in the minority carrier diffusion length
and hence to an overall degradation of the device (panel)
performance. There are some approaches to minimize this
deleterious effect, for instance by pumping between the p- and
the i-layers which slows down the thruput of panel production
even further.

Whilst this techniques was a viable technology in the late
1970's and early 1980's, it is no longer considered state-of-
the-art approach towards mass production.

3.2.2   Roll to Roll Approach

In this so called roll to roll approach, two types of
substrates are under investigation, polyemide and stainless
steel. These have a major drawback for several reasons. In
this, a roll is fed thru the system, so that p-, i- and n-
layers are deposited sequentially as the substrate is fed down
the line. This by necessity leads to a cross contamination due
to Boron (from the p- layer depositon section) and Phosphorus
(from the n-layer deposition section) and leads to the

degradation in the opto-electronic properties of the i-layer and consequently in the device (panel) performance. Although various schemes exist to minimize the cross contamination, such as the use of gas curtains between the p- and i-layers, nevertheless it should be recognised that even one part per million of Boron (or Phosphorous) severely affects the properties of the i-layer. Other drawbacks to this approach are that the use of both substrates require the deposition of the TCO after the p-i-n deposition which therefore limits the processing temperature to 250°C. It is generally found that the TCO becomes more resistive at lower temperatures and inclusion of this will decrease the power from the panel due to increased electrical losses. If this temperature is exceeded, H would evolve from a-Si:H layers thus leading to a dramatic increase in the defect densities within the semiconductor (a-Si:H) and hence lead to a severe degradation in the device performance. Using a ployemide substrate requires extensive prebake procedures in order to expel the H_2O componant from within the substrate. Using an expensive stailess steel substrate prevents a panel formation, as in Fig. 6, since by definition an insulating substrate is reqtried. Using this substrate, the cells are cut into strips and subsequentally joined to effect a series connected panel which slows down the production process and increases costs; this approach totally ignores the encomous advantages that a-Si technology has to offer and that is the ability to produce minolithic panels, as in Fig 6, during the production process.

3.2.3 Continuous - Multichamber Approach

As discussed above, the roll to roll and the batch approaches either lead to a low thruput or cross contamination problems leading to low performance cells. Hence, just as in the R&D approach where high efficiency cells can be produced using the multichamber approach, such that the deposition of p-, i- and n-layers occurs in chambers which are completly separated, the same can then be achieved also in the mass production process, shown schematically in Fig. 8. In order to provide a continuous thruput, Fig. 9 shows the layout of GSI's continous p-i-n a-Si:H segment which consists of three building blocks: Load Lock Module (LLM), Isolation Module (IM), and a Deposition Module (DM). All the chambers are integral in terms of transporation, gas handling, pumping etc. The substrate can be moved, at different speeds in the chambers to maximize thruput whilst the IM's and the gate valves ensure zero cross contamination to ensure maximum performance from the panels. The actual GSI's system for production is shown in Fig. 10. Using this approach it is envisaged that the cost of production will be in the range of $1.50-$2.00 per watt within the next two years. With expected improvement in the efficiencies, the cost of production will be brought down even further, to below $1/Watt, in the next 2-3 years.

4.0 Future Trends

It is of interest to note that the U.S. DOE/SERI have recently
announced a major initiative in the a-Si based photovoltaic
area with the stated goals of 18% laboratory type efficiency
and 13% efficiency over a sq. ft. area by 1989. This will
naturally provide a major impetus to the work being performed
here and worldwide. The effort will cover virtually every
aspect of this technology. Materials (wide and narrow band
gap) such as a-Si:Ge, a-Si:Sn, a-Si:C, a-Si:N will be
synthesised and the role of defect creation will be studied
thoroughly. The role of superlattices, microcrystalline n^+ and
p^+ layers will be investigated more throughly in device
configurations. New ideas, as to the removal of weak Si-Si
bonds will be investigated. There will be an intense interest
in vastly boosting the deposition rates, improving process
technology, faster scribing techniques, more efficient use in
material utilization, etc. With the realization of the DOE
goals, a-Si based technology could contribute significantly to
the energy production and its full potential will then be
realized.

5.0 Role of Research in Developing Countries

As shown in Table 2, in the initial stages, the major
deployment of this technology is expected to be in the
developing countries. This will occur by way of installation
of panels and arrays as well as the installation of complete or

partial panel production plants. As discussed in Section 3.0, a turn key photovoltaic manufacturing plant involves the integration of many technologies. Hence, these plants will need R & D backup for support as well as to provide an improvement in the process to give better yields, performance, reliability etc. Further, these plants will require skilled personnel which no doubt the indigenous Universities and Institution can supply. It was mentioned in Section 4.0, that the major effort in the U.S. in the next couple of years will be concentrated on improving and synthesizing new materials to boost the conversion effieincy to 18%. The U.S. has already extablished a very strong R & D base in this type of technology; the developing countries are then faced with different options. They could continue to import new technologies and without their own R & D base they are then perpetually reliant on U.S. or Japan. Faced with the fact that turnkey plants are likely to be installed in their own countries, then it is an ideal opportunity for them to set up their own R & D. This cuold be via the purchase of a system such as GSI's, which sells the system with complete know how to obtain state-of-the-art materials and devices and thus minimize the learning curve time. In addition, there are many groups in the U.S./Japan who may have an interest in setting up collaborative effort with their counterparts in the developing countries. It would thus appear, that the developing countries are in excellent position to acquire this technology and use this as a base to make their contribution in the years ahead.

Further they could position themselves to provide a leadership in this exciting high technology field and also provide some form of energy independence for their countries. As mentioned in the Introduction, a-Si has many different applications, hence the acquisition of this new technology can also lead to major growth industries in their own countries.
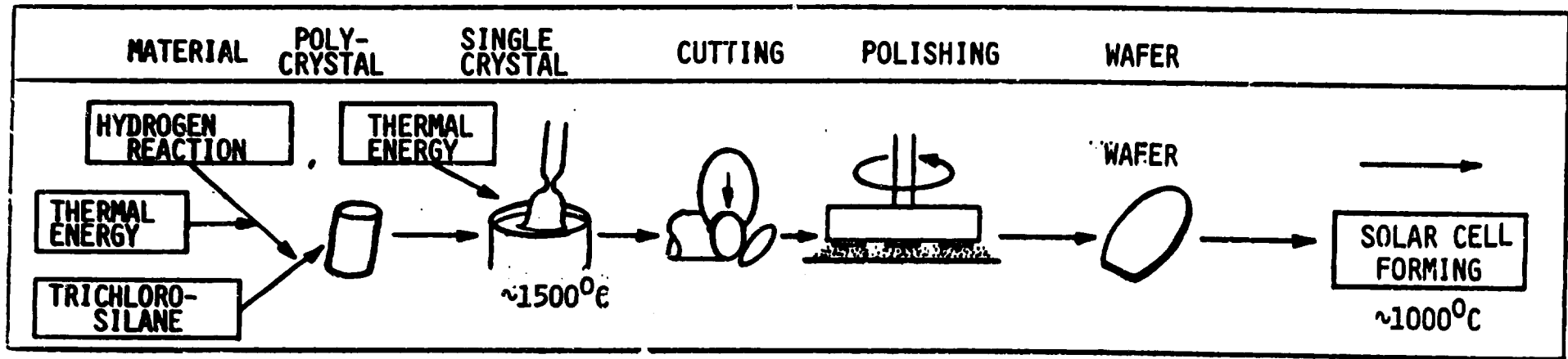
MATERIAL	POLY-CRYSTAL	SINGLE CRYSTAL	CUTTING	POLISHING	WAFER

HYDROGEN REACTION

THERMAL ENERGY

THERMAL ENERGY

TRICHLORO-SILANE

~1500°C

WAFER

SOLAR CELL FORMING

~1000°C

Fig. 1   SINGLE CRYSTAL Si PROCESS STEPS

World PV Shipments

Legend:
- ■ Amorphous Silicon
- ▨ Polycrystalline Silicon
- ⊠ Single Crystal Si, Flat Plate
- ⊞ Concentrator & Other
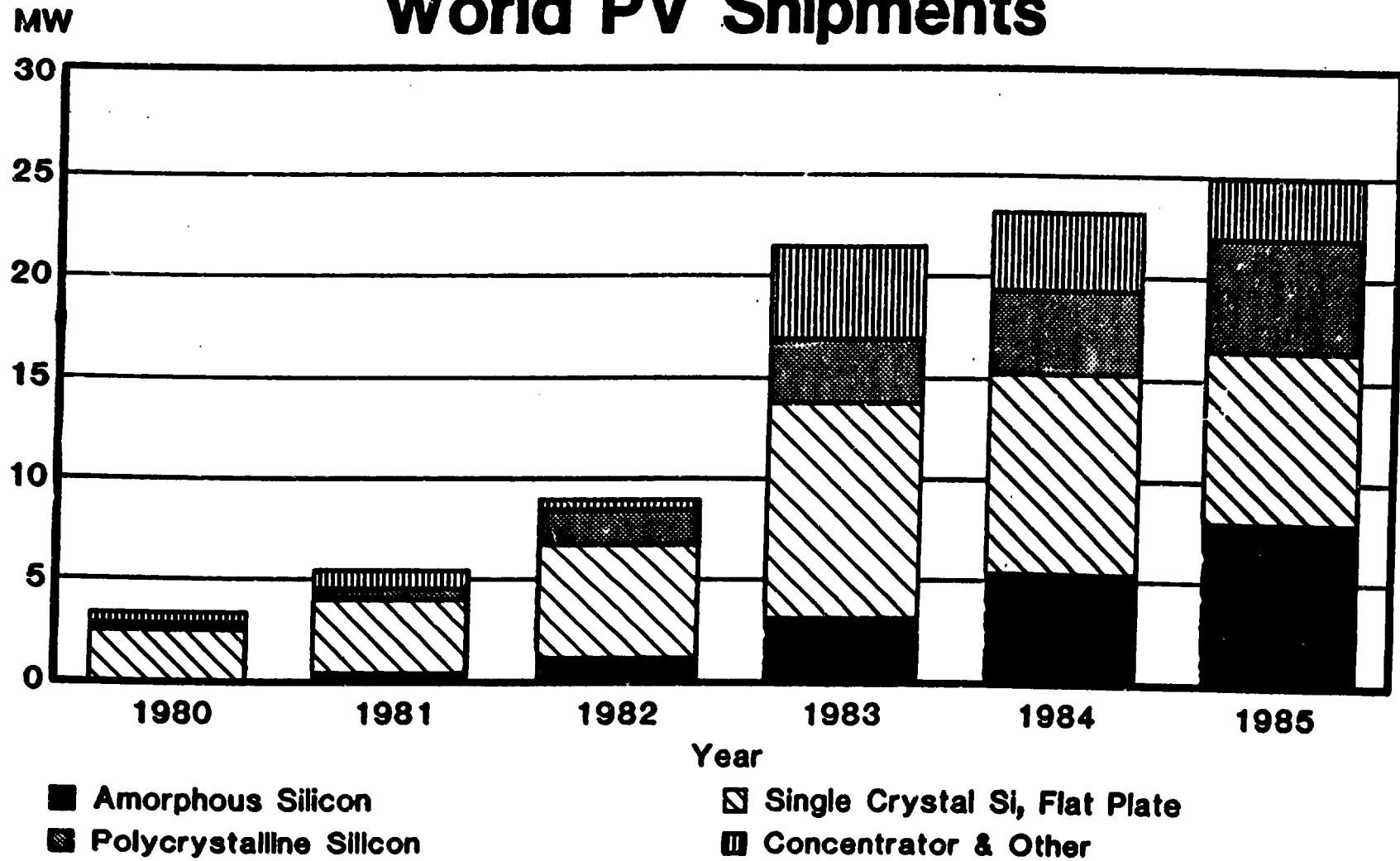
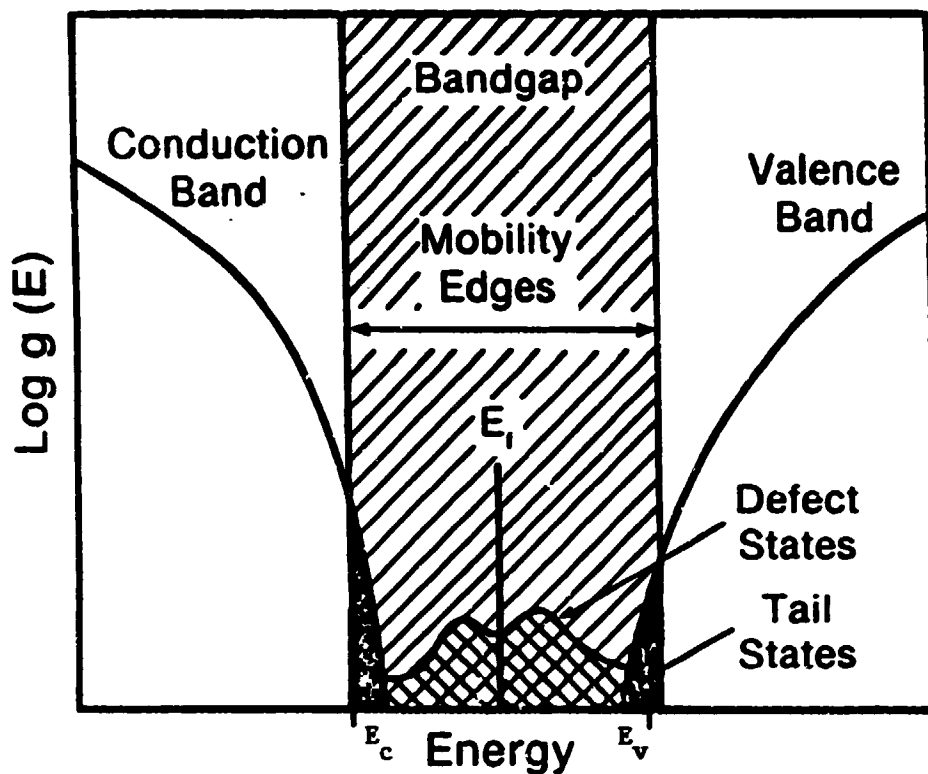Fig. 2   World Photovoltaic Shipment shown by type of technology. (Source: U.S. Department of Energy, 1985)

Fig. 3 Distribution of density of states, g(E), in
amorphous semiconductors.

Fig. 4   A photograph of a GSI state of the art, multichamber
PECVD system for amorphous silicon deposition.   The
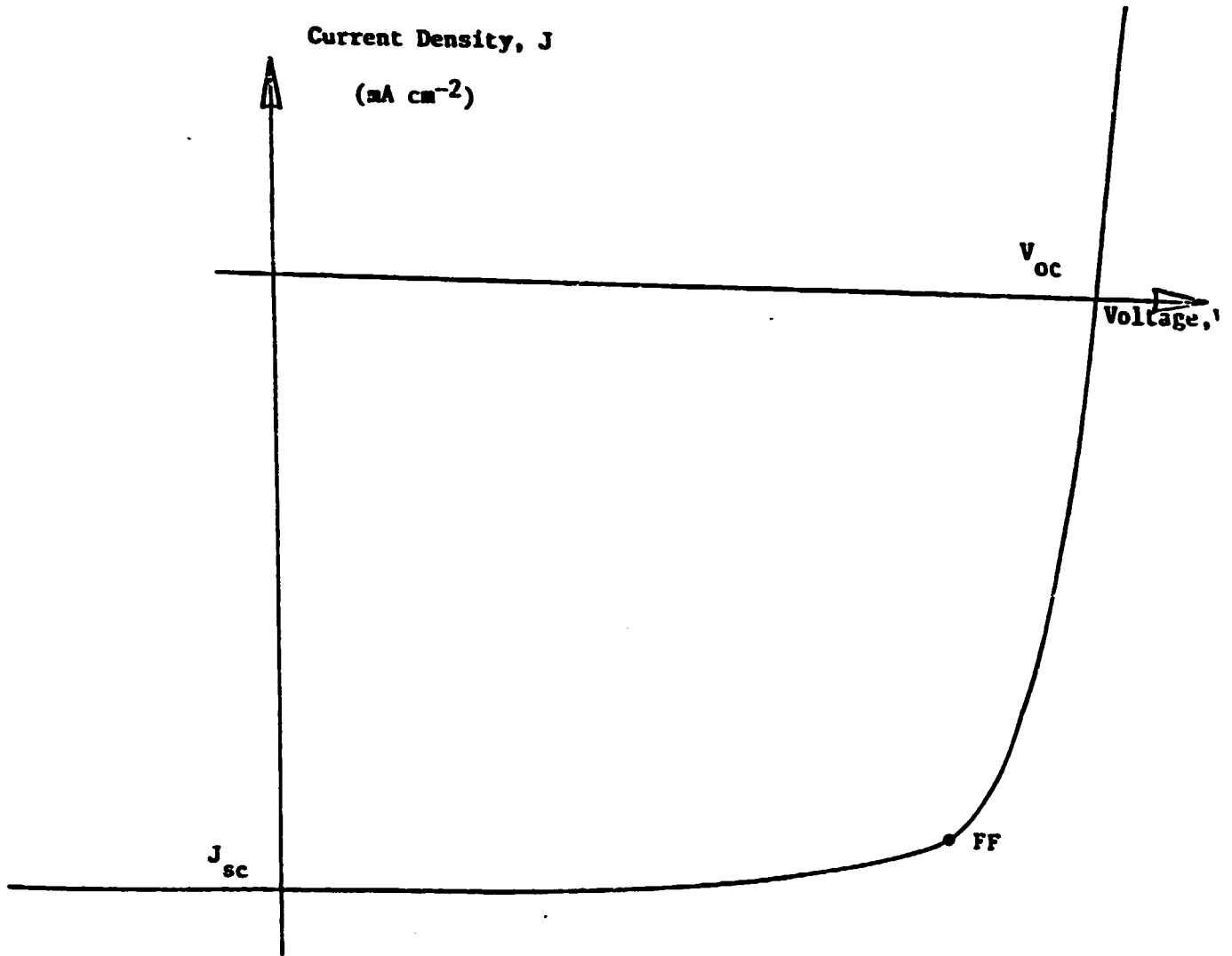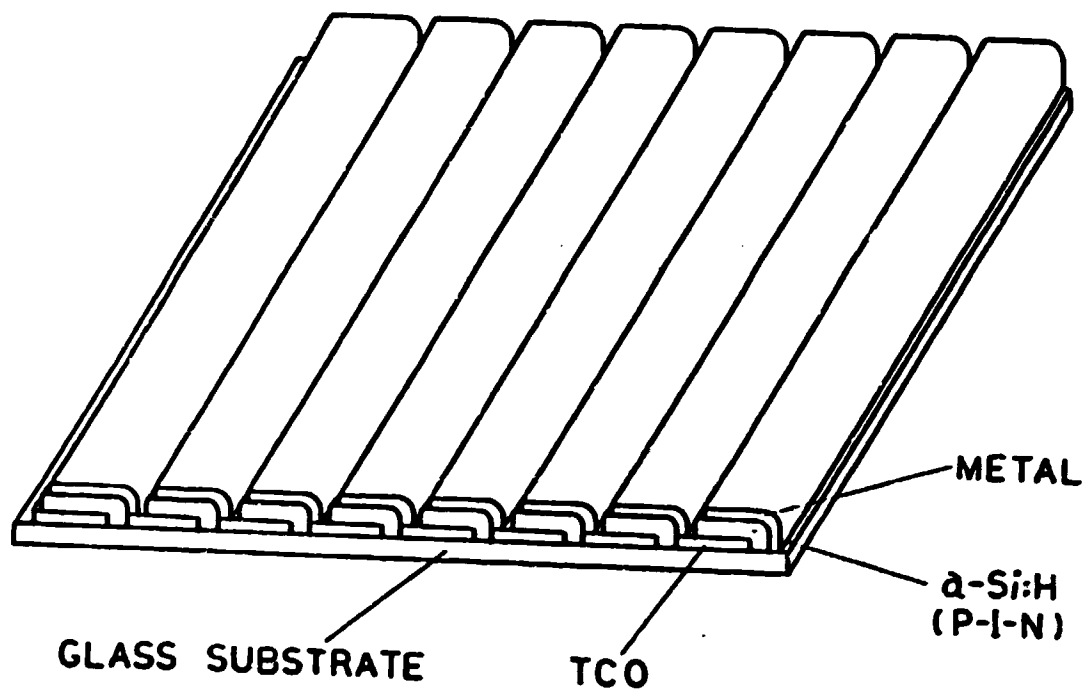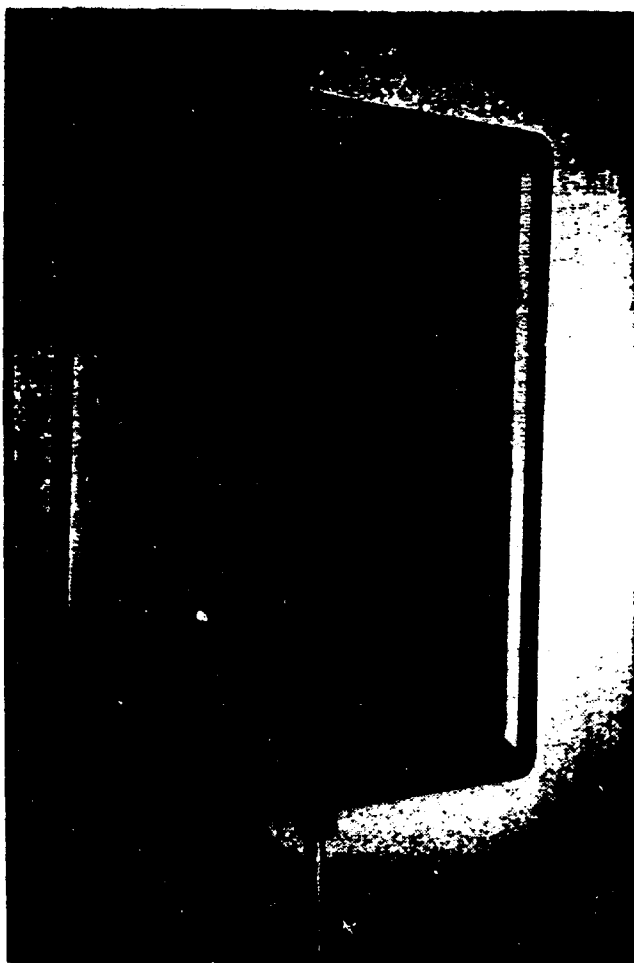silane plasma can be seen.

Fig. 5   Current – voltage characteristics of a solar cell

METAL

a-Si:H
(P-I-N)

GLASS SUBSTRATE   TCO

Fig. 6   Construction of a monolithic Amorphous Silicon panel on an
         inexpensive glass substrate.

Fig. 7 Large area Arco Solar Genesis module rated at 6%
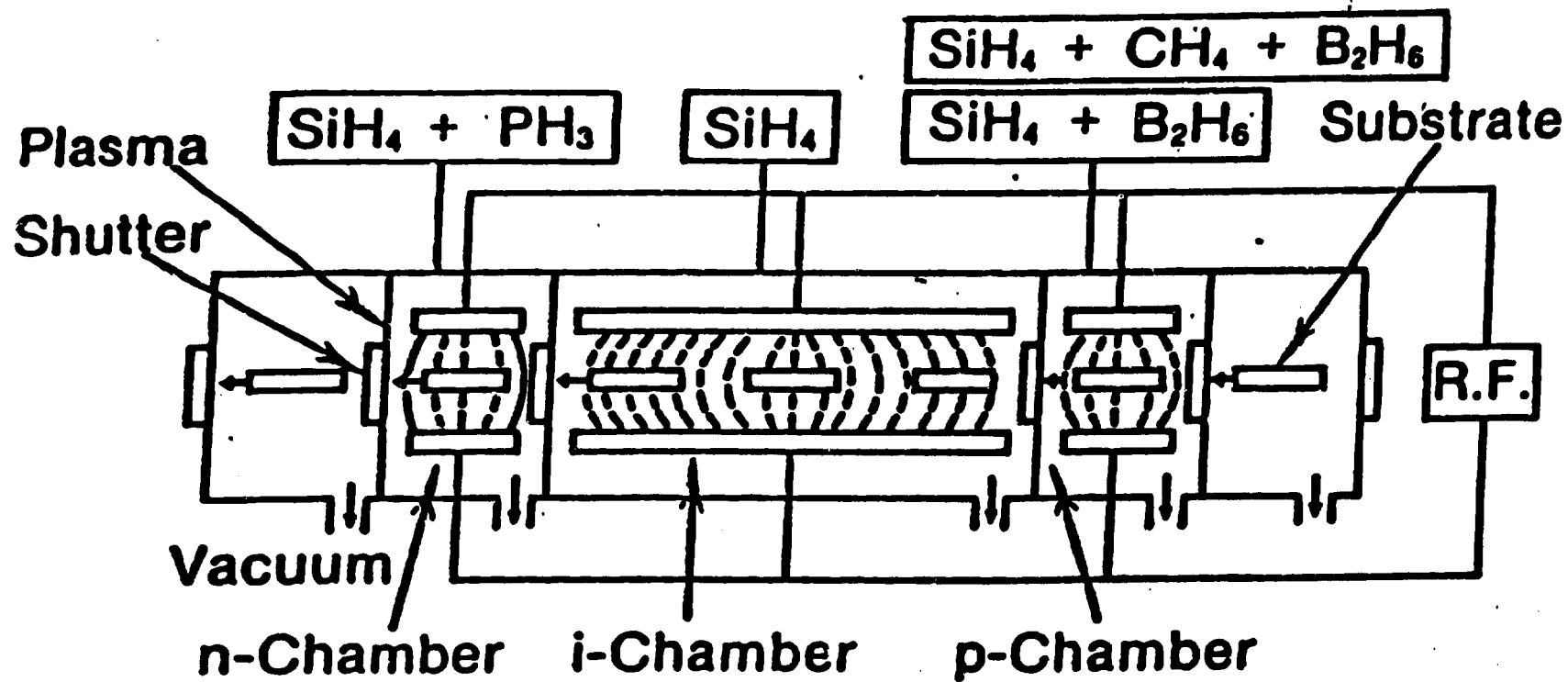conversion efficiency.

Fig. 8 Schematic of a multichamber production system for the deposition of p-, i-, and n- layers.
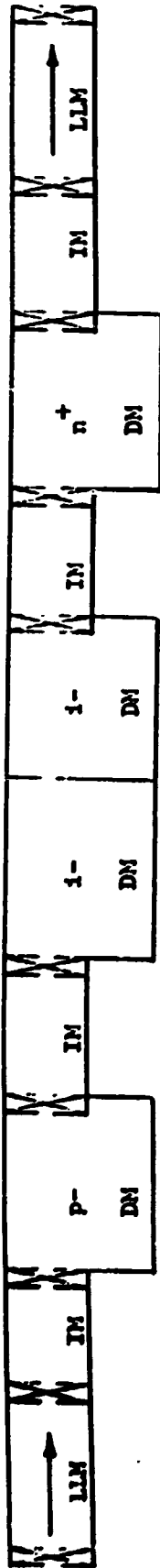
Fig. 9   Schematic of a GSI continuous p-i-n Amorphous Silicon Line.   (X, Gate Valve;
LLM, Load Lock Module; IM, Isolation Module; DM, Deposition Module).

FIG. 10   GSI'S MULTICHAMBER SYSTEM FOR CONTINUOUS IN-LINE MASS
PRODUCTION OF LARGE AREA AMORPHOUS SILICON SOLAR PANELS

GLASSTECH SOLAR, INC.

12441 West 49th Ave,
Wheatridge, CO. 80033

Current PV Technology Summary and 1985 Production Figures

| Cell Type | Efficiency | | Advantages | Disadvantages | 1985 Production by Company (MWe)[1] | | | |
	Lab. Record	Prod. Range						
Single Crystal Silicon	19.1%	10-13%	• Well established and tested technology • Stable • Relatively efficient	• Uses a lot of expensive material • Lots of waste in slicing wafers • Costly to manufacture • Round cells can't be spaced in modules efficiently	Arco Solar (US) Sharp (Japan) CEL (India) Hoxan (Japan) Solec Int'l (US) BP Solar (UK) Pragma (Italy) Ansaldo (Italy) Nippon Elec (Jap) Solarex (US)	4.7 .9 .6 .5 .4 .4 .3 .3 .3 .2	Helios (Italy) Hitachi (Jap) Mitsubishi (Jap) Kyocera (Jap) Heliodynamica (Braz) Bharat (India) Silonex (Canada) Siemens (Germany) Isophoton (Spain) Komatsu (Japan) Other Total	.2 .2 .2 .2 .2 .2 .1 .1 .1 .1 .4 10.85
Polycrystal Silicon	18%	10-12%	• Well established and tested technology • Stable • Relatively efficient • Less expensive than single crystal Si • Square cells for more efficient spacing	• Uses a lot of expensive material • Lots of waste in slicing wafers • Fairly costly to manufacture • Slightly less efficient than single crystal	Solarex (US) Photowatt (Fr) AEG (Germany) Solavolt (US) Kyocera (Jap) Pragma (Italy) Other Total	1.9 1.0 .8 .5 .4 .2 .1 4.9		
Ribbon Silicon	15%	10-12½%	• Does not require slicing • Less material waste than single crystal and polycrystal • Potential for high speed manufacturing • Relatively efficient	• has not been scaled up to large-volume production • Complex manufacturing process	Mobile Solar (US) Westinghouse (US) Total	.1 .05 .15		
Amorphous Silicon	11½%	4-8%	• Very low material use • Potential for highly automated and very rapid production • Potential for very low cost	• Staebler-Wronski effect	Sanyo (Jap) Fuji (Jap) ECD/Sharp (Jap) Arco Solar (US) Chronar (US)	3.9 2.8 .5 .2 .2	Kaneka (Jap) Taiyo Yuden (Jap) Solarex (US) Sovonics (US) Other Total	.2 .15 .1 .1 .3 8.45

1. Figures from PHOTOVOLTAIC NEWS, February, 1986, Vol. 5, No. 2
Edited by Paul D. Maycock and Edward N. Stirewalt

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TABLE 2: SUMMARY OF WORLD MARKET FORECAST

SOURCE: PHOTOVOLTAIC ENERGY SYSTEMS, INC. (1985)

MARKET SECTOR	1984	1990	1995
WORLD CONSUMER PRODUCTS	5	50	75
US OFF-THE-GRID RESIDENTIAL	2	20	50
WORLD OFF-THE-GRID RURAL	0.2	5	30
WORLDWIDE COMMUNICATIONS	5	5	30
WORLDWIDE PV/DIESEL	2	100	1125
US GRID-CONNECTED RESIDENTIAL	0.1	3	20
US CENTRAL STATIONS & THIRD PARTY-FINANCED PROJECTS	10	240	350
TOTAL (MW)	24.3	458	1900
JAPANESE GRID-CONNECTED	---	40	100
TOTAL (MW)	25	500	2000
PRICE ($/WP)	7	3	2
TOTAL ($M)	175	1500	4000

TABLE 3: COMPARISON OF CRYSTALLINE AND AMORPHOUS SEMICONDUCTORS

CRYSTAL	AMORPHOUS
PERIODIC	NON PERIODIC
HIGH TEMPERATURE PROCESS	LOW TEMPERATURE PROCESS
INDIRECT	DIRECT
~100μm TO ABSORB LIGHT	<1μm TO ABSORB LIGHT
INTERCONNECTS TO PRODUCE MODULES	NO INTERCONNECTS MONOLITHIC MODULES
SIZE LIMITATION	NO SIZE LIMITATION
INHERENTLY WASTEFUL OF EXPENSIVE MATERIAL	VIRTUALLY NO WASTE

Table 4(a)   Conditions for a-Si:H deposition using glow
discharge (PECVD) technique.

Gas Composition	SiH_4
Deposition Temperature	$250^{o}C$
Radio Frequency Power	
Dissipation	$20mWcm^{-2}$
Anode-Cathode Distance	2-4 cms
Flow Rate	40-150 sccm
Deposition Pressure	100-500mTorr

—

Table 4(b)   Some opto-electronic properties of a-Si:H alloy

<u>Intrinsic Layer Properties</u>

Optical band gap, E_g	1.7eV
Dark Conductivity, σ_D,	$\sim 10^{-10}(\Omega cm)^{-1}$
Conductivity under AM-1 illumation	$>10^{-5}(\Omega cm)^{-1}$
$E_c - E_f$	$\sim 0.9eV$
DOS at the Fermi level	$\sim 10^{15}cm^{-3}eV^{-1}$
ESR spin density	$\sim 10^{15}cm^{-3}$
Photoluminescence peak at 77K	$\sim 1.3eV$
Infrared absorption peaks	$2000/640cm^{-1}$
Minority carrier diffusion length under light bias	$>0.5\mu m$

<u>Dark Conductivity Upon Doping</u>	$\sigma_D(\Omega cm)^{-1}$
n^+-layer – amorphous	$>10^{-2}$
– !crocrystalline	> 1
p^+-layer – amorphous	$>10^{-3}$
microcrystalline	>1

TABLE 5

CONVERSION EFFICIENCIES POSSIBLE WITH SINGLE AND TANDEM
JUNCTIONS

	E_{g1}(eV)	E_{g2}(eV)	V_{oc}(volts)	J_{sc}(mAcm^{-2})	FF	η(%)
SINGLE	1.7	---	1.10	21.3	0.80	18.7
TANDEM	1.7	1.0	1.56	21.3	0.80	26.6
TANDEM	2.245	1.7	2.64	10.8	0.80	22.8

Appendix A

Some Basic Concepts of Amorphous Semiconductors

Amorphous semiconductors, such as a-Si based alloys, are generally prepared in a metastable state and are to be distinguished from glassy materials which are highly viscous liquids. The success of the energy band theory in predicting the semiconducting behavior of a solid has relied on the derivation of the energy-wave vector (E-k) relationship. This involves the consideration of a periodic array of atoms and the formulation of Bloch wave functions from which the class of states available to electrons and holes can be predicted leading to the concept of a forbidden gap. Implicit in these treatments is that the periodicity of the atomic structure is vital. However, the resistivity, and hence the carrier transport, is observed not to change at the melting point, where the periodicity is lost and the density of the material changes markedly. Since there is not change in the electrical characteristics at the melting point then the long range periodicity is apparently not of great. importance. For example, from X-ray and electron diffraction experiments, it is found that the nearest neighbor environments of a-Ge and a-Si are approximately the same as those found in their crystalline counterpart. Beyond the second neighbor environment, any resemblance to their crystalline counterpart ceases.

However, the atomic disorder, inherent in amorphous
semiconductors, does have some effect on the opto-electronic
properties, providing distinct differences between them and
crystallin materials. The introduction of disorder results in
scattering that leads to a finite mean free path, L, of the
carriers. If the disorder is increased such that L is on the
order of the interatomic distance, a, the wave function of the
carriers will fluctuate randomly, at which point k is no longer
a good quantum number. With a further increase in disorder,
the wave function decays exponentially at a rate dictated by
the disorder potential and the carriers are then localized. L
approximately equal to a represents the demarcation (critical
energy, E_c) between localized and non localized states. Hence,
the energy band picture can be visualized, as shown in Fig. 1,
where E_v and E_c define the critical energies, for the valence
and conduction bands respectively. In this, the conduction for
$E \leq E_c$ occurs by hopping within the localized states with a low
mobility (typically $< 10^{-3}$ cm^2 s^{-1} V^{-1}) and in the non-
localized states ($E > E_c$), the transport occurs via extended
states with a much higher mobility ($\mu \sim 1 \sim 10$ cm^2 s^{-1} V^{-1}).
The major distinguishing feature of an amorphous semiconductor
is the band of tail states due to the inherent disorder. This
causes a change in the carrier transport, at the critical
energies E_c and E_v, leading to the concept of mobility edge and
hence to a mobility gap, E_c-E_v; it is this aspect which
provides for the semiconducting behavior. Further, it should

be emphasized that there are additional localized states situated in the mid gap region which are due to dangling bonds and are more a function of the processing conditions.