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Multijunction amorphous silicon solar cells

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ABSTRACT

Thin-film multijunction solar cells have the potential to meet the performance and cost requirements for grid-connected power generation. At present, multijunction amorphous silicon solar cells have exhibited stabilized conversion efficiencies of about 10% in the laboratory, and large-area modules of comparable performance should be available commercially by the mid-1990s. Further improvements in the properties of amorphous silicon alloys should lead to even-higher-performance multijunction modules in the late 1990s with manufacturing costs of less than U.S. \$0·50 W_p^{-1}.

§ 1. INTRODUCTION

The direct conversion of solar radiation into electricity via photovoltaics is one of the few energy options that does not create pollutants or hazardous wastes. However, the cost of photovoltaic (PV) power has historically been so high that it has not been able to compete with conventional sources of electricity in most applications.

This situation is rapidly changing as the manufacturing cost for producing PV modules continues to decrease, and photovoltaics is becoming increasingly cost effective as a power source in applications such as telecommunications, irrigation and in remote villages. The average selling price of PV modules has fallen from over U.S. \$100 W_p^{-1} in the early 1970s to about U.S. \$4 W_p^{-1} in 1989. However, the price must still fall by a factor of two to three before photovoltaics will start to become cost effective with grid-connected power. The first large-scale grid-connected arrays will probably be installed in areas such as San Diego, California, where the cost of electricity is more than U.S. \$0·12 $kW^{-1}\,h^{-1}$ and the solar isolation is relatively high.

Thin-film solar cells such as a-Si appear to be promising candidates for grid-connected power stations or PV roofing. However, the PV modules will need to exhibit conversion efficiencies of at least 10%, have operational lifetimes greater than 20 years and cost about U.S. \$1 W_p^{-1} or less. Present commercial a-Si PV modules exhibit stable conversion efficiencies of only 4–5%. It appears that even with further improvements the performance of single-junction a-Si PV modules will be limited to stabilized efficiencies of less than 6%.

An approach that has already demonstrated stabilized conversion efficiencies of about 10% in the laboratory involves the use of multijunction or stacked-junction device configurations using alloys of a-Si. In this paper, some of the fundamental principles underlying multijunction cells are discussed and device structures based on a-Si as well as the performance of these devices reviewed. The paper concludes with a discussion of the reliability, stability and costs of multijunction a-Si PV modules.

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§ 2. Efficiency limits of multijunction solar cells

In principle, the conversion efficiency of a PV device can be close to 100% under certain conditions. This is the case for an ideal diode exposed to monochromatic light with the photon energy close to the semiconductor bandgap and operating at a temperature near absolute zero.

The difficulty with PV conversion of sunlight into electricity is that the solar spectrum encompasses a wide range of photon energies. Thus, many of the photons have energies less than the semiconductor bandgap and are not absorbed, and many of them have energies greater than the bandgap with the excess energy being converted into heat. For a single-crystal silicon solar cell with a bandgap of 1·1 eV, a loss of about 24% in conversion efficiency occurs because of photons that have energies less than 1·1 eV, and a loss of about 32·5% occurs because of heat generated by photons with energies greater than 1·1 eV (Wolf 1981).

At room temperature, the operating voltage of a solar cell is less than the bandgap even in an ideal diode because of the thermal nature of the diffusion current in a diode. Thus the theoretical limit for the conversion efficiency of a single-crystal silicon solar cell is about 29% at room temperature in normal sunlight (Green, Wenham and Blakers 1987). The best conversion efficiency demonstrated in the laboratory for such a cell is about 23% (Green, Wenham, Zhao, Zolper and Blakers 1990).

It is possible to obtain even higher conversion efficiencies by stacking semiconductor junctions of increasing bandgaps one on top of the other. In the simplest case of a two-junction device, the top junction consists of a wide-bandgap semiconductor that absorbs the high-energy photons and allows the transmission of lower-energy photons to the bottom junction where they are absorbed. If these junctions are grown one on top of the other, then the junctions are in series, and each junction must be configured so that the photocurrents are equal. For such a two-terminal device, the theoretical conversion efficiency is estimated to be about 36·2% at room temperature in normal sunlight (Fan, Tsaur and Palm 1982). If the junctions are fabricated separately but are optically connected in series, then the theoretical limit of the conversion efficiency of such a four-terminal device is slightly higher (36·6%). In both cases, the optimum device would have a top junction with a bandgap of 1·75 eV and a bottom junction with a bandgap of 1·1 eV.

For triple-junction structures, the theoretical limits are about 41·1 and 42·5% for two- and four-terminal devices respectively. The optimum bandgaps are about 1·0, 1·5 and 2·05 eV for three junctions.

Table 1. Performance and optimum bandgaps for multijunction solar cells under 1000 suns concentration.

Number of junctions	Device efficiency (%)	Bandgaps (eV)
1	32·4	1·4
2	44·3	1·0, 1·8
3	50·3	1·0, 1·6, 2·2
4	53·9	0·8, 1·4, 1·8, 2·2
5	56·9	0·6, 1·0, 1·4, 1·8, 2·2
6	58·5	0·6, 1·0, 1·4, 1·8, 2·0, 2·2
7	59·6	0·6, 1·0, 1·4, 1·8, 2·0, 2·2, 2·6
8	60·6	0·6, 1·0, 1·4, 1·6, 1·8, 2·0, 2·2, 2·6

Table 2. Performance of multijunction a-Si solar cells.

Conversion efficiency (%)	Structure	Organization
16·8	a-Si/poly-Si (four terminal)	Osaka University (Japan)
15·6	a-Si/CIS (four terminal)	ARCO Solar (U.S.A.)
13·7	a-Si/a-Si/a-$Si_{1-x}Ge_x$	Sovonics (U.S.A.)
12·4	a-Si/a-Si/a-$Si_{1-x}Ge_x$	Sumitomo (Japan)
11·3	a-Si/a-Si	Fuji Electric (Japan)
11·2	a-Si/a-Si	Kanegafuchi (Japan)
10·5	a-$Si_{1-x}C_x$/a-$Si_{1-x}Ge_x$	Solarex (U.S.A.)

The conversion efficiency of solar cells can be improved by operating either at lower temperatures or at higher light intensities. Bennett and Olsen (1978) showed that the conversion efficiency of multijunction solar cells could exceed 60% at room temperature when exposed to a light intensity of 1000 suns. Table 1 lists some of their results showing that an efficiency of 60·6% is the limit for a device with eight junctions of the proper bandgaps.

§ 3. Performance of multijunction thin-film solar cells

In recent years, most organizations working with thin-film solar cells have started to focus their efforts on multijunction devices because of their potential for high stabilized conversion efficiencies. As shown in table 2, conversion efficiencies in excess of 10% have been obtained in several different multijunction device configurations.

The simplest multijunction device is a same-bandgap structure which stacks two or more a-Si p–i–n junctions in series (Hamakawa, Okamoto and Nitta 1979). In this case, the thicknesses of the i layers are adjusted so that the photocurrents from each junction are equal and, since the photovoltages are additive, these devices deliver higher voltages but smaller current densities than single-junction solar cells do. For a triple-junction structure, the thicknesses of the i layers might be 40, 90 and 500 nm in order to balance the photocurrents in normal sunlight. (The bandgap of hydrogenated amorphous silicon (a-Si : H), containing about 10 at.% H, is about 1·75 eV; all device-quality a-Si alloys are deposited from glow discharges containing silane and other appropriate gases.)

Same-bandgap multijunction a-Si devices can outperform single-junction a-Si solar cells since they exhibit less light-induced degradation. All device-quality a-Si films exhibit an increase in metastable defects when exposed to light (Staebler and Wronski 1977). These metastable defects are Si dangling bonds that can be annealed out after several minutes at 200°C. The concentration of these metastable defects appears to saturate at a concentration of about 10^{+17} cm^{-3} after several months of sunlight (Park, Liu and Wagner 1989). The stability of a-Si solar cells improves as the cells are made thinner (Hanak and Korsun 1982) since the metastable defects are actually created by recombination and trapping of photogenerated carriers; the strong electric field in a thin device sweeps out the carriers before recombination or trapping can occur. Thus a multijunction a-Si cell will exhibit better stability than a single-junction cell of comparable total thickness does.

As mentioned in the previous section, multijunction solar cells have the potential of very high efficiencies if the bandgaps of the various junctions are chosen properly. As shown in table 2, conversion efficiencies as high as 13·7% have been obtained in triple-junction cells where the bottom p–i–n junction uses an amorphous silicon–germanium alloy (a-$Si_{1-x}Ge_x$) (Yang *et al.* 1988). In these devices, the bandgap of the a-$Si_{1-x}Ge_x$ i layer is graded from about 1·72 eV near both the p–i and i–n interfaces to a bandgap of about 1·45 eV near the centre of the i layer (Guha *et al.* 1988).

A diagram of this triple-junction structure is shown in fig. 1 (*a*). The top contact is a transparent conductive oxide (indium tin oxide (ITO)) which also acts as an antireflection layer. The back contact is a zinc oxide/silver reflector that efficiently reflects weakly absorbed light back into the active layers. The p layers are boron-doped microcrystalline silicon films deposited by glow-discharge deposition in an atmosphere of silane, silicon tetrafluoride, diborane and hydrogen (Guha, Yang, Nath and Hack 1986). In some cases, the n layer might also be microcrystalline silicon (phosphorus-doped) and, in other cases, the p layer might be an amorphous silicon–carbon (a-$Si_{1-x}C_x$) alloy with a bandgap of about 2·0 eV (Yoshida, Yamanaka, Konagai and Takahashi 1987).

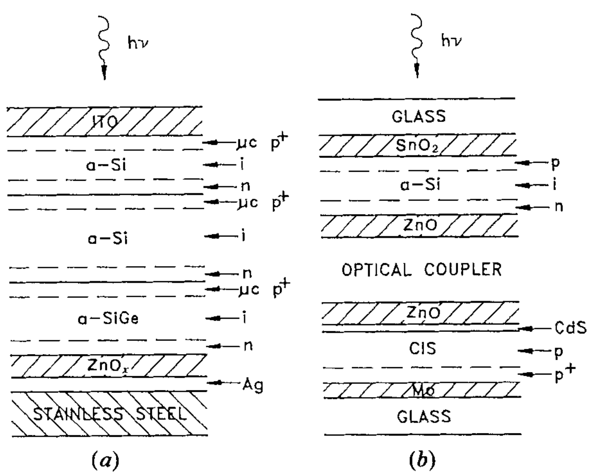
Since this type of multijunction solar cell has three junctions in series, the open-circuit voltage V_{oc} under normal sunlight is 2·55 V compared with about 0·85 V for a single-junction a-Si solar cell (Yang *et al.* 1988). The short-circuit current density J_{sc} of the 13·7% cell was 7·66 mA cm^{-2} and the fill factor FF was 0·701. The fill factor relates J_{sc} and V_{oc} to the maximum power point, $P_{max} = V_{max}J_{max} = FFJ_{sc}V_{oc}$. The conversion efficiency can be expressed as

$$n = FFJ_{sc}V_{oc}/P_i, \quad (1)$$

where P_i is the power density of sunlight incident on the solar cell (about 100 mW cm^{-2}).

Another version of a triple-junction cell uses an a-$Si_{1-x}C_x$ in the i layer of the top junction with a-Si in the second layer and a-$Si_{1-x}Ge_x$ in the bottom cell. Conversion efficiencies of 9·0% have recently been obtained in 1 ft^2 modules using this

Fig. 1



Diagrams of multijunction thin-film solar cells: (*a*) a two-terminal triple-junction structure with a bottom junction containing an a-$Si_{1-x}Ge_x$ i layer; (*b*) a four-terminal, optically coupled a-Si/CIS multijunction structure.

configuration (Catalano 1990). The bandgaps of the three i layers were 1·45, 1·75 and 1·9 eV. Further improvements in the electronic properties of the a-$Si_{1-x}Ge_x$ and a-$Si_{1-x}C_x$ layers should lead to significantly higher performances in this type of structure. Kuwano *et al.* (1982) have estimated that a conversion efficiency of 24% might be obtained with this type of multijunction solar cell.

In the last few years, impressive results have been obtained with two-junction four-terminal devices. A conversion efficiency of 15·6% has been reported in a multijunction cell (4 cm^2) where the top a-Si p–i–n cell is optically coupled to an underlying CdS/$CuInSe_2$ (CIS) cell (Morel *et al.* 1988). The device structure is shown schematically in fig. 1 (*b*). Moreover, a conversion efficiency of 12·3% has been achieved in an a-Si/CIS multijunction module with an aperture area of 843 cm^2.

Another type of two-junction four-terminal device that has exhibited good performance is one where an a-Si p–i–n junction is placed over a polycrystalline silicon p–n junction (Matsumoto, Miyagi, Takakura, Okamoto and Hamakawa 1990). A conversion efficiency of 16·8% has been obtained in this type of multijunction cell.

§4. The stability and reliability of a-Si multijunction solar cells

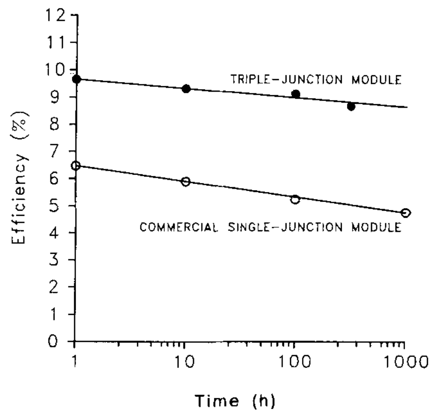
a-Si-based multijunction solar cells exhibit less light-induced degradation than do single-junction a-Si cells for several reasons. First, as mentioned in the previous section, thin p–i–n junctions are less susceptible to degradation since the strong electric field in a thin i layer sweeps out the photogenerated carriers before they can create metastable defects via trapping or recombination. In a-Si multijunction solar cells, the top junction is usually quite thin (of the order of 100 nm or less) so that light-induced degradation in this junction is usually negligible.

Bennett and Rajan (1988) have shown that the light-induced degradation of a multijunction solar cell can be described by averaging the degradation expected for the individual junctions under similar illumination conditions. Since the top junction is relatively stable, the stability of a multijunction cells will always be superior to a single-junction cell even if one of the junctions in the multijunction cell is comparable in thickness with the single-junction cell. Another factor influencing the stability of multijunction cells is that the lower junctions do not receive as much light as a single-junction cell does and therefore degrade more slowly even if the thickness is comparable.

The more advanced a-Si multijunction cells use a-$Si_{1-x}Ge_x$ alloys in the i layer of the bottom junction. These alloys exhibit very little light-induced degradation when the germanium content exceeds about 30 at.% (or the optical gap is less than about 1·5 eV) (Stutzmann, Street, Tsai, Boyce and Ready 1989). At present, the situation is reversed with a-$Si_{1-x}C_x$ alloys where the degradation increases with increasing carbon content (Crandall, Carlson, Catalano and Weakliem 1984). This behaviour appears to be related to the inhomogeneous microstructure of a-$Si_{1-x}C_x$ films (Williamson, Mahan, Nelson and Crandall 1989), and considerable effort is under way at a number of laboratories to improve the properties of these films.

Performance data for single-junction and multijunction PV modules as a function of illumination time are shown in fig. 2. The data are plotted on a logarithmic time scale where 1000 h of constant illumination (100 mW cm^{-2}) is comparable with about a year of outdoor operation. Other studies have shown that, after a year of operation, a-Si solar cells tend to stabilize; the performance varies with the seasons as some annealing of metastable defects occurs during the summers (Matsuoka *et al.* 1990). As shown in fig. 2, the performances of the multijunction devices are far better than the single-

Fig. 2



The conversion efficiency as a function of illumination time for a single-junction a-Si module ($1000\,cm^2$) and a triple-junction a-Si/a-Si/a-$Si_{1-x}Ge_x$ module ($100\,cm^2$).

junction devices after 1000 h of illumination. At present, the best a-Si multijunction solar cells exhibit a stabilized performance of about 10% (Ichikawa, Fujikake, Yoshida, Hama and Sakai 1990).

The reliability of a-Si multijunction solar cells depends not only on their resistance to light-induced degradation but also on their ability to withstand adverse environmental conditions. The prospects for developing a-Si multijunction PV modules with a lifetime greater than 20 years appears to be good since present single-junction a-Si PV modules are able to pass a battery of environmental tests. Some of these tests are as follows: cycling the modules 250 times between −40 and 90°C; soaking the modules for 4 weeks at 85°C (85% relative humidity); hitting the modules with 1 in ice balls to simulate hail impact; subjecting the modules to a high voltage (greater than 1500 V) while wet (Carlson 1988).

§ 5. Manufacturing costs

A number of studies have projected that the cost of manufacturing single-junction a-Si solar cells should fall to below U.S. \$1 W_p^{-1} when plants are built with capacities of about $10\,MW_p\,year^{-1}$ (Carlson, O'Dowd and Oswald 1989). (The term peak Watt (abbreviation, W_p) refers to the power produced by a solar cell when exposed to normal sunlight ($100\,mW\,cm^{-2}$).) However, some of these studies assumed that the conversion efficiency would be 10%, and a stabilized performance of that level now seems unlikely for single-junction modules. Moreoever, even if module costs of less than U.S. \$1 W_p^{-1} are obtained for low-performance modules, the total system cost of an array may be prohibitive owing to the cost of the balance of system (e.g. land costs, support structures and wiring).

The process for manufacturing multijunction a-Si modules is somewhat more complicated than that for single-junction modules. The major difference is that two or more p–i–n junctions must be deposited in a glow-discahrge deposition system, and feedstocks such as germane must be used to grow alloy films such as a-$Si_{1-x}Ge_x$. For multijunction modules, additional deposition chambers must be added to the glow-discharge system to assure adequate throughput. These chambers would add about U.S. \$300 000–450 000 to the total equipment cost of about U.S. \$10 000 000. At present, germane is an expensive feedstock at U.S. \$7 g^{-1} compared with silane at U.S. \$0·23 g^{-1}. For a triple-junction module of 10% efficiency with a bottom junction containing a-$Si_{1-x}Ge_x$, germane adds about U.S. \$0·05 W_p^{-1} to the material costs.

Assuming that the manufacturing plant has a capacity of 10 MW_p $year^{-1}$ and produces 10%-efficient 2 ft × 4 ft triple-junction modules in a computer-integrated-manufacturing line, the total manufacturing costs for frameless modules is estimated to be about U.S. \$0·57 W_p^{-1} (Carlson *et al.* 1989). As shown in table 3, the cost of materials is over 55% of the total manufacturing cost. The total cost could be reduced still further by increasing the conversion efficiency beyond 10% or by building even larger plants and integrating a float-glass plant into the facility (for capacities of about 100 MW_p $year^{-1}$ or greater).

§ 6. Future directions

Some studies (DeMeo and Taylor 1984) indicate that photovoltaics will only make significant inroads into the grid-connected utility power market once the conversion efficiency of PV modules reaches about 15% and the cost decreases to less than about U.S. \$1 W_p^{-1}. Can thin-film PV modules satisfy these conditions? As discussed in the previous section, the manufacturing cost of a-Si multijunction PV modules is likely to approach about U.S. \$0·50 W_p^{-1} even at conversion efficiencies of 10%.

Achieving module efficiencies of 15% requires conversion efficiencies of about 17% in small-area cells. As shown by Kuwano *et al.* (1982), a conversion efficiency of 24% is possible in a triple-junction cell if the electronic properties of the wide-bandgap (a-$Si_{1-x}C_x$) and narrow-bandgap (a-$Si_{1-x}Ge_x$) materials is comparable with high-quality a-Si : H. These alloys are generally inferior to a-Si : H apparently owing to the presence of microvoids, clusters of like atoms and hydrogen complexes. Recent work at a number of laboratories has resulted in improved electronic properties of a-$Si_{1-x}Ge_x$ alloys by employing techniques such as hydrogen dilution of the silane–germane discharge atmospheres which has led to more homogeneous films (Bennett, Catalano, Rajan and Arya 1990).

However, further improvements are needed in the properties of a-$Si_{1-x}Ge_x$ alloys and especially a-$Si_{1-x}C_x$ alloys. Thus efforts are under way at some laboratories to grow these alloys by other techniques such as photochemical vapour deposition (Yoshida *et al.* 1987) and magnetron sputtering (Rudder, Cook and Lucovsky 1983). Another approach involves using other types of feedstock gas such as silylgermanes and silylmethanes in glow-discharge atmospheres (Fieselmann, Mulligan, Wilczynski, Pickens and Dickson 1987).

Another area of investigation involves the growth of microcrystalline silicon films from glow-discharge atmospheres containing mostly hydrogen. These types of film are

Table 3. Summary of manufacturing costs.

	Cost per peak Watt (U.S. \$ W_p^{-1})	Percentage of total (%)
Materials	0·313	55·4
Depreciation	0·104	18·4
Other indirect costs	0·083	14·7
Labour	0·065	11·5
Total	0·565	100·0

especially attractive for use as doped layers in the connective p–n junctions of multijunction cells. Even more promising is the development of microcrystalline alloys such as microcrystalline silicon–carbon alloys (Hattori *et al.* 1987), but these films appear to be difficult to grow and have not yet been incorporated into multijunction structures.

At the present level of a-Si technology, it seems likely that 10% efficient a-Si multijunction modules will be available commercially in the mid-1990s and will penetrate some of the grid-connected utility markets. Further research and development should lead to multijunction modules of much higher performance by the end of the decade. When coupled with energy storage techniques, such as the electrolysis of water to generate hydrogen (Ogden and Williams 1989), photovoltaics will be positioned to play a major role in generating pollution-free energy in the next century.

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