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Novel Materials and Devices for Sunlight Concentrating Systems

Abstract: Photovoltaic conversion under concentrated sunlight is a highly promising technique that could make solar-electric power generation economically competitive with fossil fuel power generation by the mid-1980s. An economic analysis has been performed which demonstrates that solar cell efficiency, concentrator efficiency, and concentrator cost are the most important parameters in a concentrating photovoltaic system; solar cell cost is only of secondary importance (at least for Si solar cells). Six novel structures are described, including modified conventional Si cells, $Ga_{1-x}Al_xAs/GaAs$ devices, interdigitated cells, vertical and horizontal multijunction cells and "multicolor" devices.

Introduction

The conventional silicon (Si) solar cell consists of a p-type substrate of 1 to 10 ohm-cm resistivity, a thin n^+ diffused region, an ohmic contact on the back side, and a grid ohmic contact on the front side. These cells can be 18 percent efficient at 1 sun intensity ($\approx$ 100 mW/cm^2), but their efficiency decreases at higher intensities due to series resistance. Slight modifications to this conventional structure, primarily a lower base resistivity (0.3 ohm-cm) and a carefully designed grid pattern, have resulted in efficiencies of 15 percent for devices operating at 30–50 suns [1, 2], and efficiencies in the 20–22 percent range can ultimately be expected from these modified conventional Si cells.

The interest in nonconventional materials and devices stems from the possibility of higher conversion efficiencies, easier array interconnections, or improved behavior at high temperatures compared to the conventional structures. Devices such as vertical multijunction (VMJ) or interdigitated Si solar cells eliminate the series resistance and grid shadowing losses, and could have efficiencies in excess of 25 percent. Gallium arsenide (GaAs) cells could reach 26–27 percent efficiency and behave well at temperatures up to 300°C. "Multicolor" cells consisting of stacked p-n junctions of several materials or several kinds of junctions placed side by side and illuminated through spectrum-splitting filters can reach over 40 percent efficiency in theory. Finally, multijunction cells such as the VMJ or the horizontal multijunction (HMJ) produce high voltage outputs rather than high current outputs, reducing the problems of array interconnection to achieve the needed final voltage and current levels.

In the first part of this paper, the economic advantages of high efficiency solar cells for sunlight concentration systems are illustrated. In the second part, the theoretical *limit conversion efficiencies* of single-junction solar cells are calculated as a function of temperature and intensity. In the last part, the individual novel devices and their particular advantages and disadvantages are described.

Economic advantages of concentrating systems

Qualitatively, the economic advantages of sunlight concentrating systems are well known; one can replace expensive solar cell area with low cost concentrator area and still derive about the same total power output. Backus and co-workers [3] have made cost calculations of photovoltaic systems using one-axis tracking trough concentrators and have shown that levelized busbar electricity costs of 5 to 6 cents per kWh (1 kWh = 3.6×10^6 joules) might be obtainable under some conditions.

Levelized busbar ac electricity costs have been estimated in this work in order to test the sensitivity of the result to solar cell cost, cell efficiency, concentration level, and concentrator cost. The details of the computation will be given elsewhere, and the methodology is the same as that described in the ERDA/EPRI document [4]. Briefly, the method involves finding the *life cycle cost* of a concentrating central station power plant operating over a lifetime of 25 to 30 years. The life cycle cost includes the direct capital investment in the necessary equipment; an additional factor of 30 percent to account for indirect costs such as architecture and design, spare parts, contingencies, and interest during construction; and a yearly

Table 1 Assumptions in cost calculations.

Cost of:	Land	$2/m^2
	Power conditioning	$100/kW ($417/kg-cal s^{-1})
	Solar cells	variable
	Concentrators, wiring, support structure, tracking and cooling	variable
Efficiency of:	Optics	0.92, Flat plate 0.82, Concentrators
	Power conditioning and wiring	0.90
	Cells	variable
	Cooling	1.00-0.01(X/20)
Packing factor		0.35
Plant life		25 years
Operating and maintenance		$0.005/kWh
Power input (kWh/m^{2}yr)		2500, Flat plate 2640, 1-D track 3010, 2-D track
Fixed charge rate		15.2 percent

operating cost of 0.5 cents per kWh inflated at 6 percent per year. The uniform annual amount (except for distribution costs) that the power company must charge its customers each year over the lifetime of the plant is the life cycle cost multiplied by the *capital recovery factor* and divided by the total energy output of the plant. The capital recovery factor is used in accounting practice to convert a lump sum into a uniform stream of annual payments. These payments are the busbar cost of generating electricity, and include the costs of land, solar cells, concentrators and their support structures, tracking, cooling facilities, power conditioning equipment, income taxes, labor, and profit.

The key assumptions used in the calculations are shown in Table 1. By using these assumptions, the cost of generating electricity has been computed for systems without energy storage. Such systems would be useful in the southwest where the electrical demand correlates well with the peak sunlight hours.

The sensitivity to solar cell cost is shown in Fig. 1. For systems without concentration, the cell cost essentially dominates the system cost, and busbar charges of less than 5 cents/kWh are not reached unless the cell cost becomes less than $50/m^2 for an 18 percent efficient cell. The solar cell cost is much less important in concentrating systems. For two-dimensional tracking in particular, cell costs of less than $500/m^2 make little difference.

The tradeoff between solar cell efficiency and solar cell cost is demonstrated in Fig. 2. The efficiency has a much larger effect than the cost; for example, increasing the efficiency of $1250/m^2 cells from 15 to 20 percent has the same effect as lowering the cell cost to $125/m^2 or less. It is also more economical to pay $500/m^2 for cells with efficiencies of 18 percent or more than to pay $125/m^2 or less for cells which are less than 16 percent efficient. Improve-

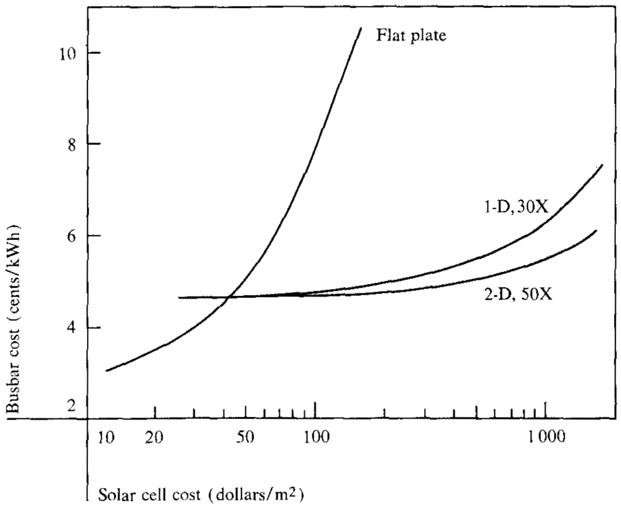

Figure 1 The effect of solar cell cost on busbar electricity generation. Flat plate: 18% cell, $20/m^2 structure and wiring. Trough concentrator (1-D): 20% cell, $60/m^2 concentrator subsystem. Two-dimensional (2-D) tracking: 20% cell, $70/m^2 concentrator subsystem.

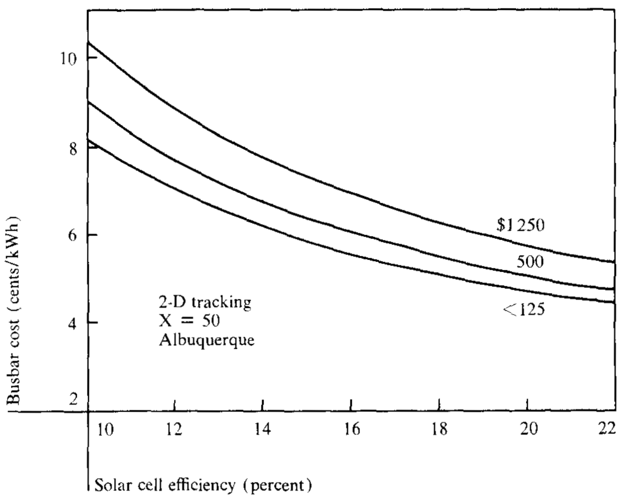

Figure 2 Busbar cost vs cell efficiency for various solar cell costs, $70/m^2 concentrator subsystem.

ments in the efficiency of the optics, the power conditioning (dc to ac inversion and maximum power point tracking), or the cooling have the same benefit as increases in the cell efficiency.

The sensitivity to the cost of the concentrator subsystem (the collector, the structural support, the tracking mechanism, and the cooling arrangement) is shown in Fig. 3. The busbar cost for two-dimensional tracking systems is less than for one-dimensional systems because of the larger amount of solar energy collected. A doubling of the concentrator subsystem cost increases the busbar cost by 40 to 50 percent.

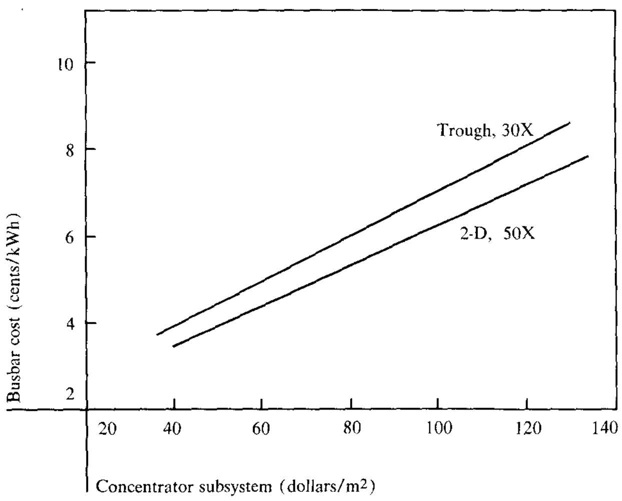

Figure 3 Busbar cost vs concentrator subsystem cost in $/m^2 of concentrator aperture. Solar cell cost $125/m^2 throughout, 20% cell.

Table 2 Device parameters, limit efficiency.

GaAs conditions, p on n	
Junction depth	6000Å (0.6 μm)
Surface recomb. vel., front*	1×10^4 cm/s
Surface recomb. vel., back	infinite
Front doping	2×10^{19} cm^{-3}
Back doping	2×10^{17} cm^{-3}
Lifetime, front region	5×10^{-9} s
Lifetime, back region	5×10^{-8} s
Thickness	100 μm
Si conditions, n on p	
Junction depth	2000Å (0.2 μm)
Surface recomb. vel., front	1×10^3 cm/s
Surface recomb. vel., back	0
Front doping	2×10^{19} cm^{-3}
Back doping	1×10^{17} cm^{-3}
Lifetime, front	0.4×10^{-6} s
Lifetime, back	20×10^{-6} s
Thickness	450 μm

*$Ga_{1-x}Al_xAs$ window layer used.

These cost calculations have been made by using particular assumptions regarding power plant life, fixed charge rate, indirect to direct cost ratio, optical, cooling, and power conditioning efficiencies, etc., and certainly other assumptions for these parameters could be made with equal validity. However, the major conclusions of the study would not be changed. These conclusions are that the solar cell efficiency, concentrator efficiency, and concentrator cost are the most important areas of concern. Solar cell cost has only secondary importance once it has been reduced to less than $400–500/m^2 of finished cells. Solar cell efficiencies of around 20 percent in concentrator systems of 30X (X = concentration in AM1 suns) or more begin to make photovoltaic systems appear economically competitive with other future means of generating peak electricity. Even higher efficiencies, obtainable by several novel approaches, could conceivably make photovoltaic systems with added energy storage competitive for intermediate-load or base-load generation.

Limit conversion efficiency

The limit conversion efficiency represents a theoretical upper limit to the efficiency that could be obtained from a solar cell for a given spectral input and for a given set of device parameters. The effect of energy bandgap on the limit efficiency has been examined in the past for different air masses [5] and different temperatures [6] for 1 sun intensity.

In this work, the limit conversion efficiency has been calculated for single junction devices as a function of bandgap (E_g), temperature, and concentration level. The method assumes 100 percent collection efficiency for all photons with energies greater than the bandgap, and computes the dark current by summing [7] the injection current and the depletion region recombination current. The value of n_i was taken as

$$n_i = [2.57 \times 10^{29} T^3 \exp(-E_g/kT)]^{\frac{1}{2}} \qquad (1)$$

for materials with bandgaps $\geq$ 1.29 eV (GaAs condition), and as

$$n_i = [4.81 \times 10^{31} T^3 \exp(-E_g/kT)]^{\frac{1}{2}} \qquad (2)$$

for materials with bandgaps < 1.29 eV (Si condition). The parameters used in calculating the dark current are shown in Table 2.

Gallium arsenide parameters are used for materials with high bandgaps since ternary compounds of $Ga_{1-x}Al_xAs$ with $x \leq 0.4$ have bandgaps in the range 1.4 to 1.95 eV with material properties very similar to GaAs. Silicon parameters were used for bandgaps less than that of InP; however, during the calculations, it was observed that there was very little difference in the results of using either set of parameters for bandgaps in the 1.0 to 1.3 eV range.

The limit efficiencies at 300 K for concentrations of 1 to 1000 AM1 suns are given in Fig. 4. The peak in the limit efficiency lies at about 1.4 eV and rises from about 28 percent at 1 sun to nearly 35 percent at 1000 suns. For Si, the limit efficiency rises from 25 percent at 1 sun to 32.6 percent at 1000 suns.

The effect of elevated temperatures is shown in Fig. 5 for a concentration of 100 suns. The efficiency decreases with temperature because of the increase of n_i [Eqs. (1)

and (2)]. Fortunately, the enhancement of efficiency with intensity can partially offset the loss due to temperature.

The efficiency peak shifts to higher bandgaps as the temperature is increased, and becomes fairly broad. Gallium arsenide is nearly the optimum material at 300 K but not at 500 K or above. The effect of temperature is much more severe on Si cells than on GaAs cells, and the efficiency of GaAs cells is twice that of the Si counterpart for temperatures ≥ 600 K. Limit efficiencies for the optimum material (i.e. the optimum bandgap at 600 K) are calculated to be 19 percent for 100 suns and 22 percent for 1000 suns.

The value of the limit conversion efficiency concept is in placing an upper bound on what might be expected from single-junction solar cells under various operating conditions, and in determining what the optimum bandgap might be under these conditions. The limit efficiency can never be attained in practice because of the unavoidable reflection losses, grid coverage, and, above all, series resistance loss. Practical devices are designed to minimize the losses at a selected operating level to attain the highest possible efficiency consistent with economic, processing, and reliability tradeoffs. In the following section, several types of solar cells designed for high efficiency at high sunlight concentrations are discussed.

Novel devices

In the introduction, six devices were mentioned which are capable of efficient operation at high intensities; these are $Ga_{1-x}Al_xAs$-GaAs cells, modified conventional Si devices, interdigitated cells, vertical multijunction (VMJ) devices, horizontal multijunction (HMJ) cells, and "multicolor" devices.

- *GaAs cells*

Measurements of GaAs solar cells with $Ga_{1-x}Al_xAs$ covering layers have shown them to be the most efficient type of cell to date under both concentrating and nonconcentrating conditions. Efficiencies of nearly 22 percent at 1 AM1 sun have been reported [8], rising to over 23 percent at 10 suns. Gallium arsenide cells have been operated at up to 5000 suns [9] and have been over 19 percent efficient at 1700 suns [10].

In order to determine the potential of GaAs solar cells for concentration applications, the *inherent* efficiency has been calculated as a function of temperature and intensity. This is the efficiency of a solar cell accounting for all bulk and surface losses except reflection, grid coverage, and series resistance losses. The inherent efficiency differs from the limit conversion efficiency in that photocurrent losses are included. Also, if the inherent efficiency is multiplied by 0.85 to 0.9 to account for the combined optical and series resistance losses, the result may be obtainable in practice. The inherent efficiency is

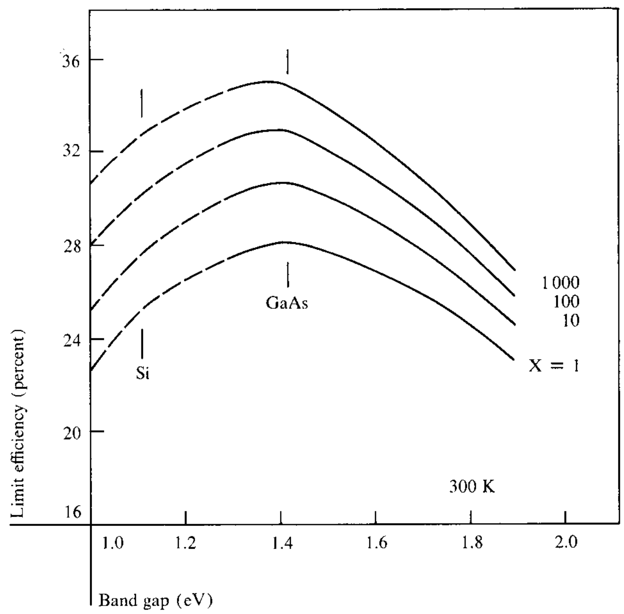

Figure 4 Limit conversion efficiency at 300 K vs bandgap and concentration. X = concentration in AM1 suns.

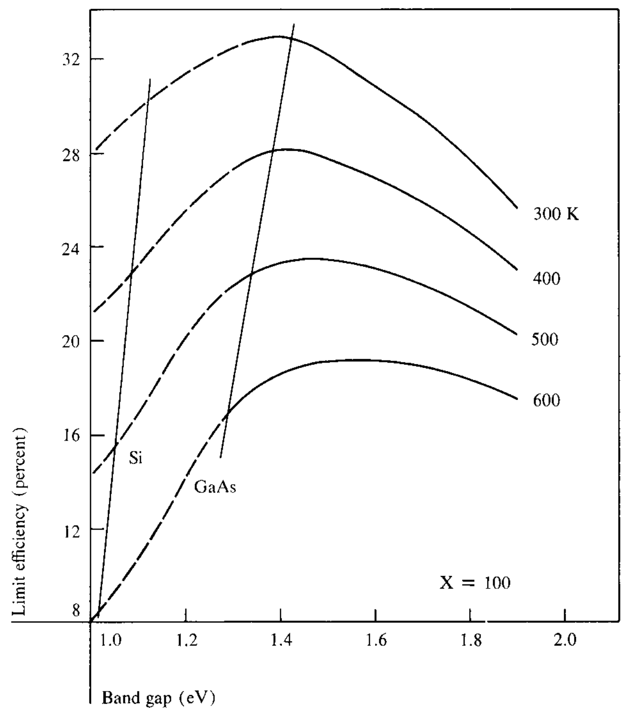

Figure 5 Limit conversion efficiency at 100 AM1 suns vs bandgap and temperature. The straight lines represent the Si and GaAs bandgaps.

calculated by using commonly observed parameters while the limit efficiency is calculated by using ideal parameters.

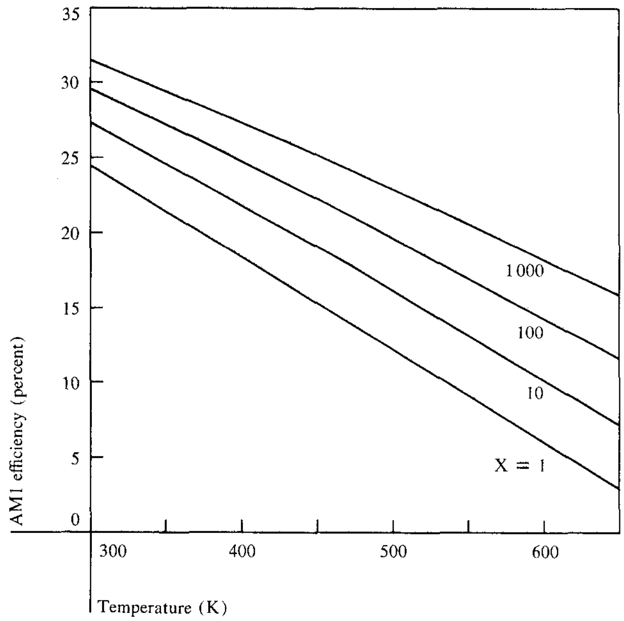

Figure 6 Calculated inherent efficiency vs temperature for several concentrations in AM1 suns.

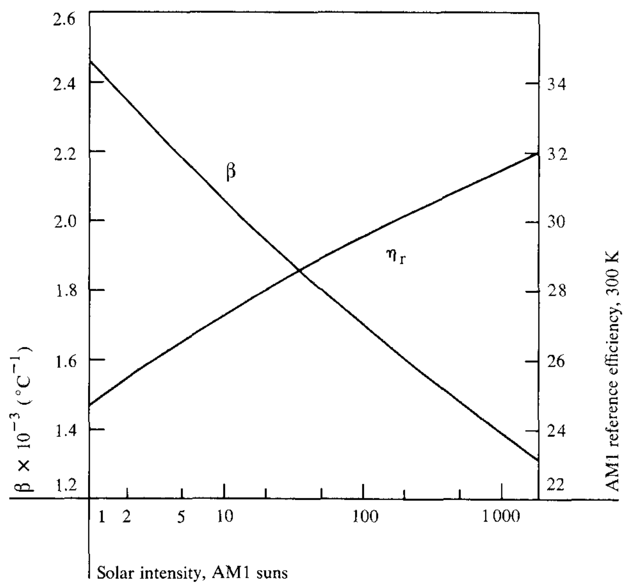

Figure 7 The slope ($d\eta/dT$) and the reference efficiency at a reference temperature of 300 K vs intensity.

The inherent efficiency of $Ga_{1-x}Al_xAs$-GaAs solar cells has been calculated by using the theory developed by Hovel and Woodall [11], the optical absorption data of Sturge [12], and the bandgap variation measured by Panish and Casey [13]. The device parameters used in the computations are given in Table 3. The photocurrent was assumed to be proportional to the intensity of the incident sunlight.

The inherent efficiency of GaAs cells vs temperature for several different concentrations is shown in Fig. 6. At 500 suns, the inherent efficiency reaches 31 percent at 300 K, decreasing to about 17 percent at 600 K. At any given concentration, the relationship can be approximated by a straight line given by

$$\eta = \eta_r[1 - \beta(T - T_r)], \qquad (3)$$

where β is the slope of the line for a constant intensity, and η_r is the known efficiency at temperature T_r. β and η_r are functions only of the concentration; calculated values of these parameters are given in Fig. 7. These values can be used to estimate the working efficiency under practical conditions (to a first approximation) by multiplying Eq. (3) by 0.85 to 0.9 to account for the optical and series resistance losses.

Gallium arsenide solar cells are very expensive compared to Si cells and cannot compete with Si for large scale terrestrial systems at low temperatures and intensities. At high intensities, however, particularly where temperatures of 150°C or more are desirable, GaAs has a considerable advantage, leading to the possibility of generating both electricity and high-grade heat in the same system. The high efficiency of GaAs cells also makes them useful for special applications where cell cost is not a major factor.

- *Modified conventional silicon cells*

Conventionally designed Si solar cells, i.e. those in which the current must flow through a thin diffused region, can be used for concentrated sunlight applications provided that the upper contact grid is modified to prevent large series resistance losses. Fossum [2] has outlined several methods for obtaining high practical efficiencies at 50–100 suns. An inherent efficiency of 26 percent is calculated in one case, with a practical efficiency of as much as 21–22 percent.

Conventional Si cells can be of four varieties: n^+-p, p^+-n, or *back-surface-field* (BSF) cells of either type. Fossum and Burgess [14, 15] have optimized the design of n^+-p Si cells, and have found that a base resistivity of around 0.3 ohm-cm results in the best performance at 50 to 100 suns and 100°C. This base resistivity (usually, 2 to 10 ohm-cm) is a compromise between better fill factors (reduced high level injection effects) and lower base dark currents for lower resistivities on the one hand, and better collection efficiency and lower emitter dark currents for higher base resistivities on the other. Cells of the p^+-n type could have the advantage of higher open circuit voltages (V_{oc}) [16] compared to n^+-p devices, but they have the disadvantage of higher sheet resistance [14]. The measured efficiencies of n^+-p cells have been up to 15 percent operating at 40 suns and 25°C.

Table 3 Device parameters for GaAs calculations.

$pGa_{1-x}Al_xAs$	Thickness	1000Å (0.1 μm)
	Diffusion length	0.27 μm
	Surface recomb. velocity	1×10^7 cm/s
	Doping level	1×10^{18} cm^{-3}
pGaAs	Junction depth	6000Å (0.6 μm)
	Diffusion length	2.3 μm
	Interface recomb. velocity	1×10^4 cm/s
	Doping level	2×10^{19} cm^{-3}
nGaAs	Diffusion length	2.5 μm
	Doping level	2×10^{17} cm^{-3}

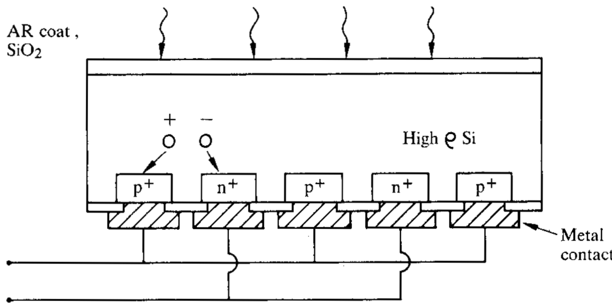

Figure 8 Interdigitated solar cell.

Back surface field cells are superior in theory to the normal n^+-p or p^+-n variety of cell [14] since the BSF cell is capable of improving the long-wavelength response and since high level injection effects are expected to enhance the V_{oc} and the fill factor (FF) of BSF cells rather than detracting from them as in the normal cell [14]. There has been some experimental confirmation of this by Napoli and co-workers [17], who observed efficiencies of 17.1 percent at 313 suns and 17.9 percent at 195 suns for n^+-p-p^+ devices.

The advantages of conventional Si cells for concentration lie in their high reliability (they are nearly the same as the standard Si solar cell that has been studied for 15 years) and their high expected efficiencies, possibly as much as 22 percent. Their disadvantage lies in the sheet resistance problem inherent in the thin diffused region. Several other types of Si solar cells are available that minimize or eliminate the resistance problem and have higher inherent efficiencies than the conventional Si cell.

Interdigitated cells

A schematic of an interdigitated solar cell [18] is shown in Fig. 8. The starting material is high resistivity (10–1000 ohm-cm), high lifetime Si about 75 to 150 μm thick. Alternate n^+ and p^+ "fingers" are diffused into one surface, and the opposite surface is covered by SiO_2, passivating the surface as well as acting as an antireflective (AR) coating. Various gettering steps can be incorporated during processing to improve the lifetime [18]. The p^+ and n^+ regions are connected in parallel, respectively, so the cell is in effect a single-junction device. Light enters through the upper surface and generates hole-electron pairs which must diffuse through the wafer to reach the p^+ and n^+ collecting junctions.

This structure has many advantages for concentration applications. Current no longer flows laterally through a thin diffused sheet layer, and therefore the series resistance loss is nearly eliminated. The remaining series resistance, due to carrier flow through the bulk, is reduced under high sunlight concentration by conductivity modulation. There are no ohmic contacts on the upper surface, eliminating the optical loss due to the metal grid. Unlike the conventional device, the interdigitated cell involves no tradeoff between junction doping level and spectral response. The voltage output is essentially determined by the n^+ and p^+ regions while the collection efficiency is determined by the high-resistivity bulk material. The voltage output should be greater than in the conventional structure since the *emitter efficiency* [14] should be high and since high injection levels should not cause voltage saturation. (The junction barrier height is determined by the p^+ and n^+ regions, and high injection level effects will not occur in those regions.)

There are also several disadvantages to the interdigitated cell. It is more sensitive than other cells to surface recombination, and very high lifetimes are required in the bulk region, which may rule out the use of low cost "solar-grade" starting material. In addition, heat sinking is more difficult because of the need for electrical isolation from the heat sink.

Lammert and Schwartz have studied the interdigitated cell both theoretically and experimentally [18, 19]. If lifetimes of several hundred microseconds or more can be obtained along with front surface recombination velocities of 10 cm/s or less, inherent efficiencies of 24–25 percent at 100 suns and 27–28 percent at 1000 suns are calculated. The practical efficiencies could be close to the inherent ones, since the only significant loss is the optical reflection from the top surface. Experimentally, devices of 15 percent efficiency operating at 50 to 280 suns have been obtained [18], and efficiencies of 20 percent may soon be obtained by optimizing the AR coating, metal contact, and heat sinking arrangement.

Vertical multijunction solar cells

The vertical multijunction cell (Fig. 9) is similar in some ways to the interdigitated cell. For both devices, the series resistance problem is greatly reduced compared to conventional devices, and there is no contact grid to obscure the incoming light. The spectral response of the

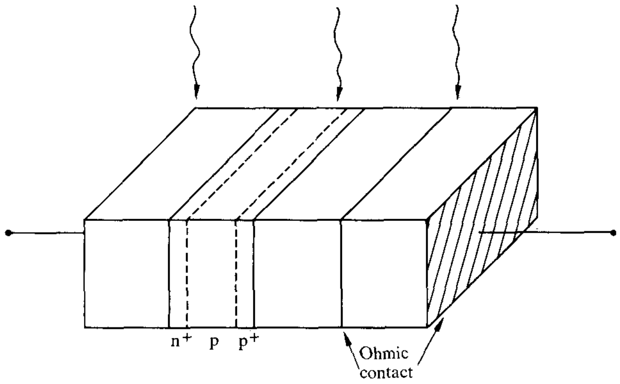

Figure 9 Vertical multijunction solar cell.

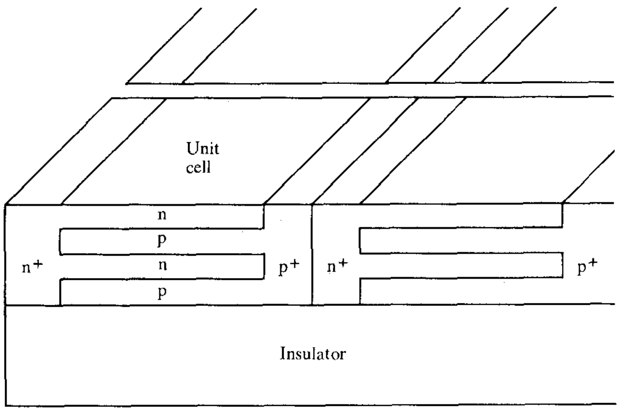

Figure 10 Silicon horizontal multijunction solar cell.

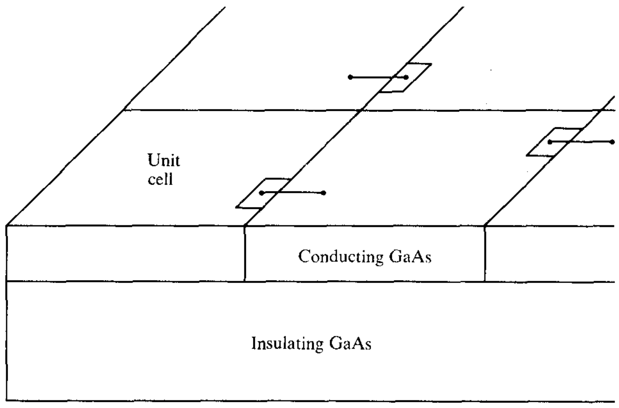

Figure 11 Horizontal multijunction solar cell in GaAs.

VMJ cell is better in theory than that of any other Si cell due to the presence of the collecting junction running vertically throughout the device. Another advantage is the inherent high voltage output of the device rather than high current output; this may simplify and lower the cost of connecting devices into arrays.

The VMJ device consists of a number of n^+-p-p^+ unit cells connected in series with ohmic metal contacts between them. The surface recombination velocity at both the top and bottom surfaces must be low for the VMJ cell to be highly efficient, and the lifetime must be sufficiently long to give a diffusion length that is several times larger than the unit cell width. The n^+ and p^+ regions and the ohmic metal connections between unit cells are photocurrent loss areas, so their widths should be minimized in relation to the overall cell width.

The series connection inherent in the cell is advantageous for array interconnection, but disadvantageous in some concentrator schemes. The light intensity must be uniform along the length of the device in order to generate equal photocurrents in each unit cell; otherwise, the current output of the entire string will be reduced to that of the worst unit. This places additional requirements on the type of concentrator used and its optical perfection. If the uniform intensity condition is met, however, the VMJ cell has the highest inherent efficiency of any of the Si concentrator solar cells.

The VMJ solar cell has been studied theoretically by Chadda and Wolf [20], Rahilly [21], and Gover and Stella [22]. The early work was aimed at developing a device with high AM0 efficiency and good radiation tolerance. More recently, the VMJ cell has been studied for concentrator applications by Sater, Goradia, and others [23–31]. Although inherent efficiencies of over 30 percent are calculated [27], the experimental efficiencies have been about 7–8 percent for devices operating at 50–200 suns [25, 28]. Analysis shows that the experimental devices are far from optimized; the unit cell widths were several times larger than the diffusion lengths, and the high loss p^+ and n^+ regions constituted 25 percent of the illuminated area. Higher resistivity material can be used to increase the diffusion lengths, or narrower individual junctions can be used. In an alternate approach, lenses can be used to focus the incoming light closer to the junction edges, substantially improving the short circuit current density (J_{sc}) [29], and increasing the efficiency in one case by a factor of 70 percent [29].

- *Horizontal multijunction cells*

The horizontal multijunction (HMJ) solar cell, like the VMJ cell, is a high voltage/low current device. In the HMJ cell, unlike the VMJ cell, the light is incident perpendicularly to the junction. Two types of HMJ cells are shown in Figs. 10 and 11. The first, as described by Warner [32], is a Si device consisting of alternate p and n layers surrounded by an n^+ region on one edge and a p^+ region on the other. The two heavily doped regions form ohmic contacts to layers of the same conductivity type, and blocking barriers to layers of the opposite type. Adjacent p^+ and n^+ regions link the separate devices in series, assuming that the doping levels are high enough for tunneling to occur. The multiple planar p-n junctions in each unit cell provide high collection efficiency at both long and short wavelengths.

The second HMJ design [33], Fig. 11, is more suitable for GaAs and other materials where p-type diffusions are simple, but n-type diffusions are difficult. The planar p-n junction unit cells are linked by metal grids into a series or parallel array or any combination of the two. (Array design can be performed on the chip for either HMJ structure to account for nonuniformities in the incident light intensity.)

Fabrication of the HMJ cell with GaAs is easier than with Si due to the existence of a semi-insulating form of GaAs. The active solar cell structure can be grown epitaxially on an insulating GaAs substrate, simplifying the electrical isolation of each unit cell from the others. For Si HMJ cells, the semi-insulating form of Si may not be of sufficiently high resistivity for good electrical isolation. One way around this is to fabricate the entire Si device separately and bond it subsequently to an insulating substrate. Another way is to use the silicon-on-sapphire structure.

The main advantages of the HMJ cell are the high voltage output and the ability to design an array directly on a chip. In addition, the series resistance problem is less than in conventional Si or GaAs solar cells, but more than in VMJ or interdigitated cells. The main disadvantage of the HMJ cell is that it is more difficult to fabricate than conventional cells, requiring several masking steps, and either epitaxial growth or multiple diffusion. The inherent efficiencies of Si or GaAs HMJ cells are about the same as those of conventional Si or GaAs cells, but the practical efficiencies may be slightly higher due to the reduced series resistance problem. To date, the HMJ device is still on the drawing board, but experimental devices should be appearing shortly.

- *"Multicolor" solar cells*

The term multicolor refers to the concept of dividing the solar spectrum into several wavelength ranges and using the optimum material for photovoltaic conversion within each range. In this way, the normally high loss due to excess photon energy can be significantly reduced, and the loss due to complete transmission at long wavelengths can be minimized.

There are two versions of the multicolor concept, as shown in Figs. 12 and 13. In the first version, the solar spectrum is partitioned by using optical filters. Each filter reflects a narrow band of wavelengths onto a suitable device and transmits the remainder onto the next filter. Alvi, Backus and Masden [34] have analyzed this approach for optimum two- and three-cell systems, and have computed limit conversion efficiencies of 37 percent for two cells and 43 percent for three cells at 1 sun. At 1000 suns the efficiencies increased to 46 and 52 percent, respectively. By using gallium arsenide, silicon, and germanium as the three devices, efficiencies of over 40 percent are predicted for either two- or three-cell combinations under concentrating conditions.

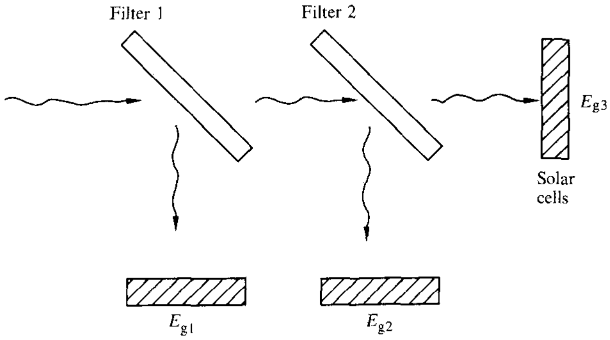

Figure 12 Spectrum splitting with multiple optical filters.

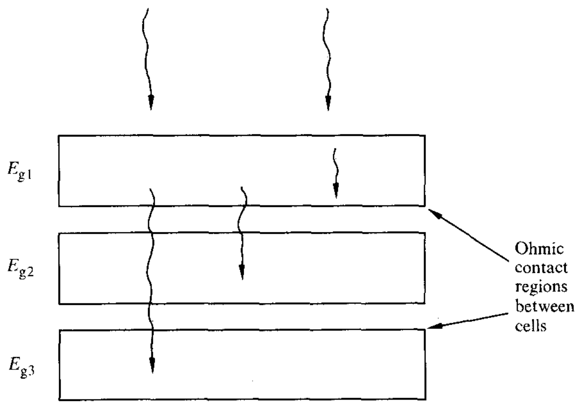

Figure 13 Stacked solar cells in optical series.

The second version of the multicolor concept (Fig. 13) has been discussed by several authors [34–38]. Solar cells of several materials are stacked together in the order of their decreasing bandgaps. Each device absorbs the photons with energies above its bandgap and transmits the rest to the cells below. The cells must be connected with ohmic regions in between to prevent photocurrent and photovoltage losses from one device to the next. The bandgaps and thicknesses must be chosen to equalize the photocurrents in each device; otherwise, three separate load circuits must be provided.

The limit conversion efficiencies of the stacked cell arrangement are slightly less than those of the optical filter approach, but are considerably greater than the efficiency of a single-junction cell. AM1 limit efficiencies of 35 to 40

Table 4 Projected and experimental efficiencies for concentrator cells.

Solar cell	*Inherent efficiency* (percent)	*Practical efficiency* (percent) *(Projected) 300 K*	*Measured efficiency* (percent)	*Ref.*
Si, n^+p	24	19–20	15 at 40 suns	2
Si, n^+pp^+	26	21–22	17 at 300 suns	17
Si, interdig.	27	24	15 at 100 suns	18
Si, VMJ	30	25	8 at 200 suns	28
GaAs, ppn	31	26	19 at 1700 suns	10
GaAs or Si HMJ		25		
Multicolor	40–50	35		

percent have been calculated [34–38] for two- and three-junction stacks without concentration. The efficiencies under concentration could reach the mid to upper 40s, while the practical efficiencies could range from 70 to 75 percent of these limit conversion values. Typical solar cell stacks might involve two or more of Ge, Si, InP, GaAs, GaP, and ternary compounds with bandgaps of several electron-volts or less.

The obvious advantage of the multicolor solar cell concept is its high efficiency. If practical efficiencies in excess of 30 percent could be achieved at any reasonable cost, the impact on the economic viability of terrestrial photovoltaics would be large. The disadvantage of the multicolor approach may be in the difficulty of fabricating the required devices. No experimental work on stacked or multifilter cells has been reported in the literature so far, but like the HMJ cell, such work should be appearing shortly.

Conclusions

Economic studies of photovoltaic solar concentrating systems suggest that busbar electrical generation costs (without storage) of 5 cents/kWh could be obtained if expected developments in solar cells and concentrators come to pass. The most important parameters in the system economics are the solar cell efficiency, the concentrator optical efficiency, and the concentrator cost; solar cell cost is of secondary importance. Several types of cells are capable of efficiencies above 20 percent, and these are listed together with their projected and present efficiencies in Table 4. Series resistance is the major problem in conventional Si and $Ga_{1-x}Al_xAs$-GaAs cells, and fine grid patterns are necessary to overcome this problem. Very high minority carrier lifetimes and low surface recombination velocities are the requirements for VMJ and interdigitated cells. (It would be valuable to study the effects of processing on lifetime in Si, and to eliminate the lifetime degradation that usually occurs during device fabrication.) Horizontal multijunction cells, like the VMJ, are high voltage/low current devices that simplify system interconnection; they have about the same inherent efficiencies as conventional cells but are more difficult to fabricate. Multicolor cells have the highest inherent efficiencies of all, and could prove to be an exciting development in terrestrial photovoltaic sunlight concentrating systems if fabrication difficulties can be overcome.

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