

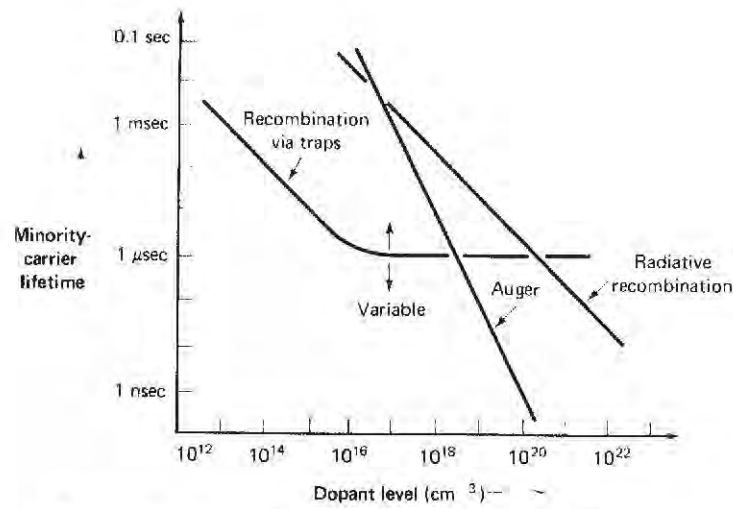


Figure 8.7. Relative magnitudes and dependence upon dopant density of minority-carrier lifetimes as determined by three competing processes for silicon.

capture cross sections of the dominant trap. For Auger recombination, the approximate expression at high doping levels is (Section 3.4.3)

$$\tau_{nA} = \frac{1}{DN_A^2} \quad (8.26)$$

while for radiative recombination (Section 3.4.2),

$$\tau_{nR} = \frac{1}{2BN_A} \quad (8.27)$$

The net recombination rate is given by

$$\frac{1}{\tau_n} = \frac{1}{\tau_{nT}} + \frac{1}{\tau_{nA}} + \frac{1}{\tau_{nR}} \quad (8.28)$$

As a consequence of the discussion above, it is concluded that increasing N_A will tend to decrease I_{SC} . Regarding the open-circuit voltage, the simple form of the expression for the saturation current density of a diode is given by Eq. (4.37)

$$I_0 = qA \left(\frac{D_e n_i^2}{L_e N_A} + \frac{D_h n_i^2}{L_h N_D} \right) \quad (8.29)$$

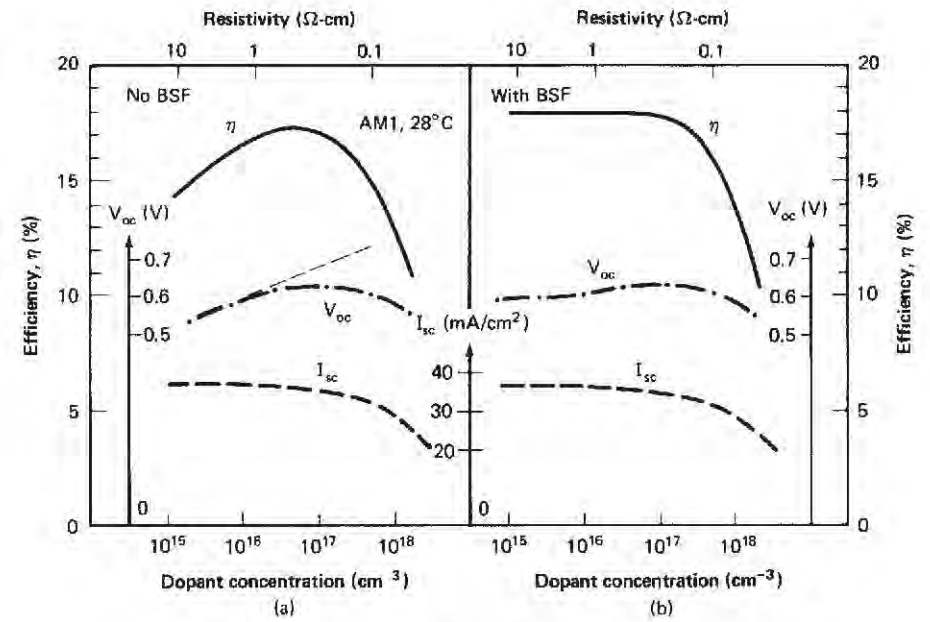


Figure 8.8. Dependence of key solar cell parameters upon the density of p -type dopants as obtained by high-performance experimental devices:

- (a) Without a back surface field.
- (b) With a back surface field.

The smaller I_0 , the larger V_{oc} . Hence, it would appear appropriate to make N_A and N_D as large as possible to obtain maximum V_{oc} . For a p -type substrate, the doping in the n -type diffused region (N_D) is made as large as possible to reduce the sheet resistivity. Hence, the second component in Eq. (8.29) is reasonably small, as discussed further in Section 8.6. It is concluded that V_{oc} will tend to increase with increasing N_A .

Because of the opposite dependencies of I_{SC} and V_{oc} upon N_A , it follows that there will be an optimum substrate doping level for maximum energy-conversion efficiency. This is in agreement with experimental results as indicated in Fig. 8.8(a). The results shown are indicative of experimental devices of good performance on substrates of different doping levels.

8.4 BACK SURFACE FIELDS

It has been mentioned that a highly doped region near the back contact will increase the short-circuit current and the open-circuit volt-

age. It improves the former by virtue of improved collection efficiency in the vicinity of the back contact, as indicated in Fig. 8.5. It improves the latter by virtue of a reduced saturation current (Section 4.9). The contribution to the saturation current from a p -type substrate with such a BSF takes the form

$$I_{0p} = \frac{qD_e n_i^2}{L_e N_A} \tanh \left(\frac{W_P}{L_e} \right) \quad (8.30)$$

Once the thickness of the p -type region is much less than a diffusion length ($W_P \ll L_e$), this equation reduces to

$$I_{0p} = \frac{qn_i^2 W_P}{\tau_e N_A} \quad (8.31)$$

With the increase of τ_e with decreasing N_A indicated in Fig. 8.7, this means that V_{oc} will not be dependent on resistivity for the higher resistivities. This differs from the case without a back surface field. Maximum efficiencies will occur at lower doping densities, provided that the series resistance of the substrate is not a problem.¹ This is indicated in Fig. 8.8(b), which shows results corresponding to Fig. 8.8(a) when a back surface field is present.

8.5 TOP-LAYER LIMITATIONS

8.5.1 Dead Layers

In Section 8.3, it was shown that high effective recombination velocities at the top surface of the cell lead to an optimal design where the top diffused layer of the cell is made as thin as possible consistent with obtaining reasonable sheet resistivities. In cells developed in the 1960s for space use, junction depths beneath the surface were typically about 0.5 μm . As much phosphorus dopant as

¹ For high resistivities, minority carrier concentrations are likely to be comparable to majority carrier concentrations during cell operation. This not only complicates the calculation of series resistance but invalidates the analysis on which the expressions of this section are based. An expression for the dark current in this case of comparable simplicity to that implied by Eq. (8.31) is (Ref. 8.1):

$$I = \frac{qn_i W_P}{(\tau_e + \tau_h)} (e^{qV/2kT} - 1)$$

possible was diffused into this thickness to keep the sheet resistivity low. This created undesirable side effects.

From simple theoretical considerations (Ref. 8.2), a Gaussian or similar distribution of phosphorus is expected within the silicon after the high-temperature diffusion step from what is essentially an infinite source of phosphorus. Figure 8.9(a) is a sketch of the distribution of electrically active phosphorus, as typically measured after different diffusion times at fixed diffusion temperature. It clearly shows an upper limit to the amount of electrically active phosphorus. This limit equals the solid solubility of phosphorus in silicon at the diffusion temperature. Phosphorus in excess of this would be expected to be incorporated into phosphorus-rich precipitates. In regions of such excess phosphorus, minority-carrier lifetimes are dramatically reduced.

In a solar cell, regions of excess phosphorus would lie near the surface of the cell. This can produce a "dead layer" near the surface where light-generated carriers have very little chance of being collected because of the very low minority-carrier lifetimes. The collection probability corresponding to this situation is shown in Fig. 8.9(b). When this problem was clearly identified (Ref. 8.3), substantial modifications in the cell design were made to produce a high efficiency cell known as the "violet" cell. Much shallower junctions were used ($\sim 0.2 \mu\text{m}$) and the surface concentration of phosphorus was kept below the solid solubility limit, eliminating dead layers. This also reduced the sheet resistivity of the diffused layer, making it essential to use much closer spacing of the grid lines of the top contact.

8.5.2 High-Doping Effects

In the heavily doped top region of the cell, minority-carrier lifetimes would be expected to be low on several accounts. From Fig. 8.7, Auger recombination would result in low maximum values for lifetimes in this region. Additionally, the possibility of precipitates and defects in the crystal structure created by the high-temperature diffusion process would increase the number of centers for recombination via trapping levels. This would decrease lifetimes below the Auger limit.

Another effect of importance in heavily doped regions is the effective narrowing of the forbidden band gap of the semiconductor (Ref. 8.4). This will have a major influence on the effective value of the intrinsic concentration, n_i .

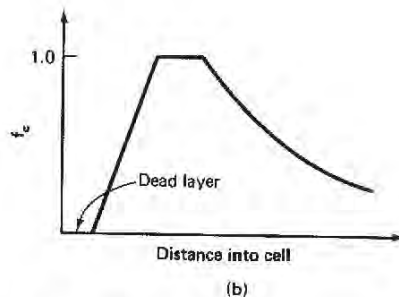
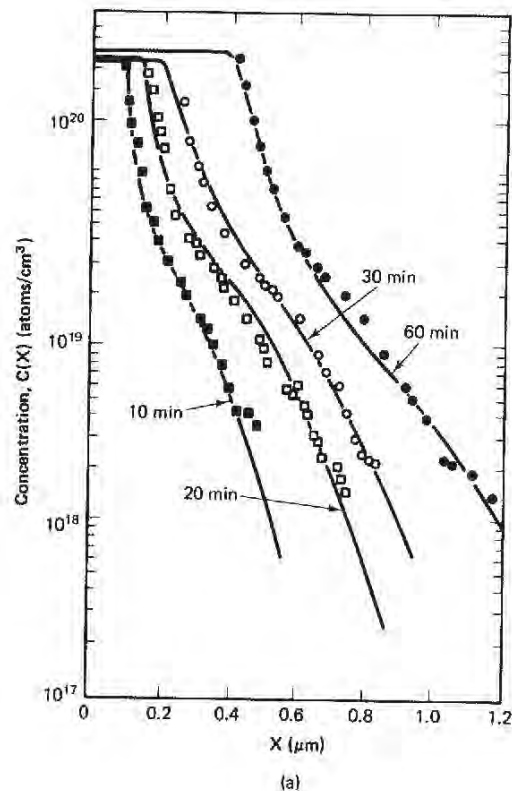


Figure 8.9. (a) Profile of electrically active phosphorus introduced into silicon for different diffusion times at fixed diffusion temperature. [After J. C. Tsai, *Proceedings of the IEEE* 57 (1969), p. 1499, © 1969 IEEE.] (b) Collection probability as a function of distance into the cell for a diffused cell with a dead layer.

8.5.3 Contribution to Saturation Current Density

In Sections 8.3 and 8.4, contributions to the saturation current density, I_0 , of the solar cell arising from the properties of the bulk region were discussed. The heavily doped top layer can also contribute significantly to this parameter.

Some general comments about the desirable properties of the top layer to minimize this contribution can be made. For example, recombination in this region and its associated surface has to be kept to a minimum. However, because of the multiplicity of effects that have to be taken into account in heavily doped regions, it is not straightforward to calculate how this is best accomplished from theoretical considerations. Experimentally, for diffused silicon cells, the minimum contribution to the saturation current density from this layer lies in the range of 1 to 3×10^{-12} A/cm². Ion-implanted top layers appear to be capable of giving slightly lower values (Ref. 8.5).

Regardless of how the substrate properties are chosen to minimize the substrate contribution to the saturation current density, the top-layer contribution will provide an upper limit to the maximum open-circuit voltage that a silicon cell of the type described can attain. This limit is in the range 600 to 630 mV at standard test conditions. The effect of this limit can be seen by referring to Fig. 8.8(a) and (b). It does not allow the full photovoltaic potential of the substrate material to be utilized. Alternative cell designs are described in Chapter 9 which overcome this limitation.

8.6 TOP-CONTACT DESIGN

One important area of cell design is the design of the top metal contact grid. This area becomes increasingly important as the size of individual cells increases. Figure 8.10 shows some of the diverse approaches to top contact design which have been used in terrestrial cells.

There are several power-loss mechanisms associated with the top contact. The loss due to lateral current flow in the top diffused layer of the cell has already been described. Additionally, there are losses due to the series resistance of the metal lines and the contact resistance between these lines and the semiconductor. Finally, there are the losses due to the shadowing of the cell by these lines.

In this section, the design of contacts for square or rectangular cells will be considered. Parallel techniques can be used for cells

A symmetrical contacting scheme such as in Fig. 8.11(a) can be broken down into unit cells as in Fig. 8.11(b). The maximum power output of this unit cell can be seen to be given by $ABJ_{mp}V_{mp}$, where AB is the area of the unit cell. J_{mp} and V_{mp} are the current density and voltage, respectively, at the maximum power point. The resistive losses in the fingers and busbars can be calculated using the integral approach as used to calculate the power loss in the top layer of the cell in Section 8.2.3. Normalized to the maximum output of the unit cell, the results are (Ref. 8.6)

$$p_{rf} = \frac{1}{m} B^2 \rho_{smf} \frac{J_{mp}}{V_{mp}} \frac{S}{W_F} \quad (8.32)$$

$$p_{rb} = \frac{1}{m} A^2 B \rho_{smb} \frac{J_{mp}}{V_{mp}} \frac{1}{W_B} \quad (8.33)$$

for the fractional resistive power loss in the fingers and busbars, respectively. ρ_{smf} and ρ_{smb} are the sheet resistivities of the contact metal layers for the fingers and busbars. In some cases these will be identical, whereas in others such as solder-dipped cells, where a thicker layer builds up over the wider busbar, ρ_{smb} will be smaller. The value of m is 4 if the respective element is linearly tapered and 3 if of uniform width. W_F and W_B are the average width of the fingers or busbar lying within the unit cell, and S is the pitch of the fingers as indicated in Fig. 8.11(b).

The fractional power losses due to shadowing by the fingers and busbar are

$$p_{sf} = \frac{W_F}{S} \quad (8.34)$$

$$p_{sb} = \frac{W_B}{B} \quad (8.35)$$

Neglecting current flows directly from the semiconductor to the busbar, the contact resistance loss is due solely to the fingers. The fractional power loss due to this effect is, as a general approximation

$$p_{cf} = \rho_c \frac{J_{mp}}{V_{mp}} \frac{S}{W_F} \quad (8.36)$$

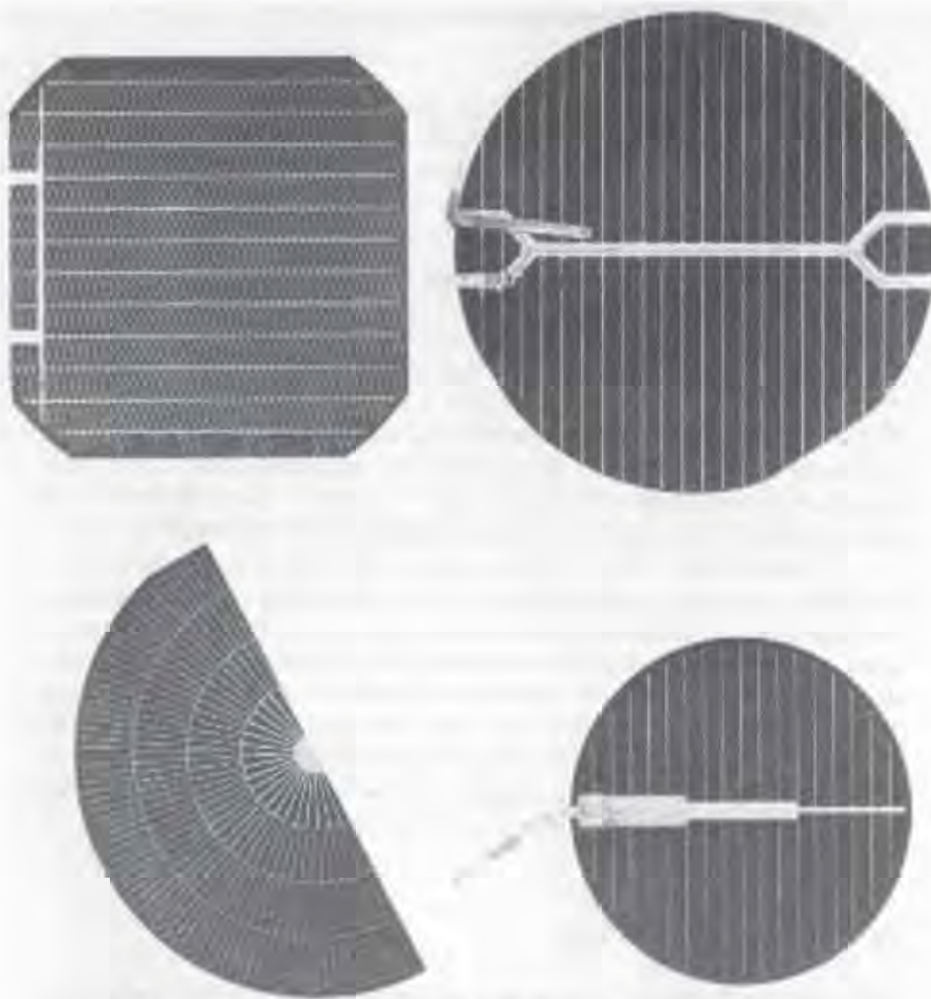


Figure 8.10. Collection of production silicon solar cells, showing diverse approaches to the design of the top contact to the cell.

of more general shape. For common contact designs, two types of metallic elements can be identified as indicated in Fig. 8.11(a). *Busbars* are relatively heavy areas of metallization directly connected to the external leads to the cell; *fingers* are finer elements which collect current for delivery to a busbar. As shown in Fig. 8.10, there can be more than one level of fingers in some cell designs. Fingers and busbars are usually either of constant width, linearly tapered, or have step changes in width.

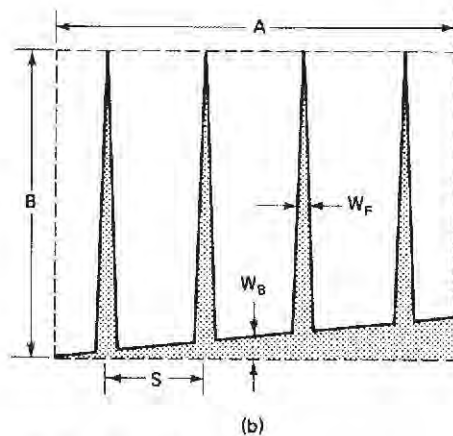
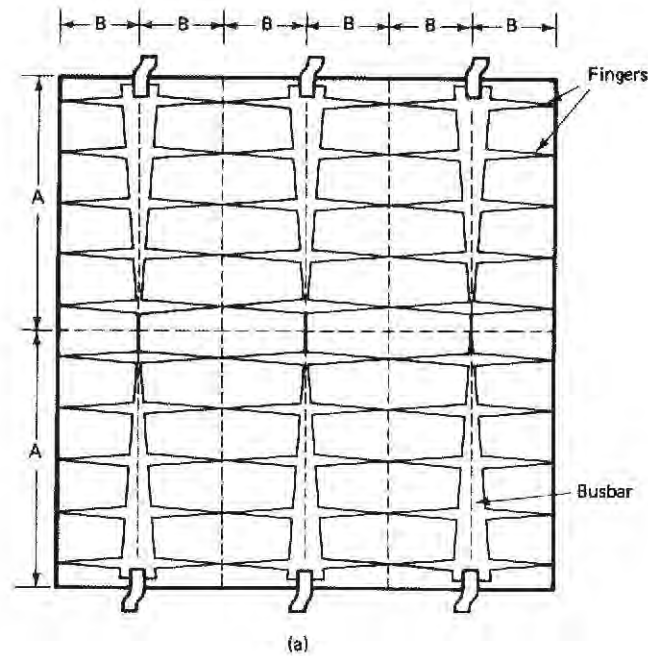


Figure 8.11. (a) Schematic of a top contact design showing busbars and fingers. Also shown is the symmetry in this particular design whereby the contact can be broken down into 12 identical unit cells. (b) Important dimensions of a typical unit cell.

where ρ_c is the specific contact resistance. Contact resistance losses are not generally an important consideration for silicon cells under one sun operation. The remaining loss is that due to the lateral current flow in the top layer of the cell. In normalized form, this is given by Eq. (8.23)

$$p_{ll} = \frac{\rho_s}{12} \frac{J_{mp}}{V_{mp}} S^2 \quad (8.37)$$

where ρ_s is the sheet resistivity of this layer.

The optimum dimensions of the busbar can be found by summing Eqs. (8.33) and (8.35) and differentiation with respect to W_B to find its optimum value (Ref. 8.6). The result is that the optimum occurs when W_B is such that the resistive loss in the busbar equals its shadowing loss. This occurs when

$$W_B = AB \sqrt{\frac{\rho_{smb}}{m} \frac{J_{mp}}{V_{mp}}} \quad (8.38)$$

with the minimum value of fractional power loss given by

$$(p_{rb} + p_{sb})_{min} = 2A \sqrt{\frac{\rho_{smb}}{m} \frac{J_{mp}}{V_{mp}}} \quad (8.39)$$

This indicates that power losses are about 13% lower when a tapered busbar ($m = 4$) is used rather than a busbar of constant width ($m = 3$).

The design of the lowest level² of finger metallization is more complex, because this also determines the lateral loss in the top region of the cell and the contact resistance losses in the cell. Mathematically, the optimum occurs when the spacing between the fingers becomes very small to make the lateral loss negligible. The optimum is then given by the conditions

$$S \rightarrow 0 \quad (8.40)$$

$$\frac{W_F}{S} = B \sqrt{\frac{\rho_{smf} + \rho_c m/B^2}{m} \frac{J_{mp}}{V_{mp}}} \quad (8.41)$$

²If there is more than one level of finger metallization, the optimum dimensions of the higher levels can be found by regarding them as the busbars for the next lowest level. Note that in this case there will be a different unit cell for each level of metallization.

$$(p_{rf} + p_{cf} + p_{sf} + p_{tl})_{\min} = 2B \sqrt{\frac{\rho_{smf} + \rho_c m/B^2}{m}} \frac{J_{mp}}{V_{mp}} \quad (8.42)$$

In practice, it will not be possible to obtain this optimum performance. Each of the technologies for forming the top contacts previously discussed will place its own limit on how small W_F and hence S can be while still maintaining acceptable yields in a production environment.

In this case the optimum finger design can be realized by a simple iterative process. Regarding the finger width W_F as fixed at some minimum value by technological limitations, the optimum value of S corresponding to this can be found by successive approximations. At some trial value of S' , the corresponding fractional power losses p_{rf} , p_{cf} , p_{sf} , and p_{tl} are calculated. A better approximation to the optimum value can then be calculated as³

$$S'' = \frac{S'(3p_{sf} - p_{rf} - p_{cf})}{2(p_{sf} + p_{tl})} \quad (8.43)$$

This process will quickly converge to a constant value corresponding to the optimum. A starting trial value for the optimum can be found by noting that the value of S calculated from Eq. (8.41) will be an overestimate. A value equal to half this should result in a stable iteration sequence.

The approach, as described above, will allow selection of the optimum dimensions of busbar and fingers once the gross features of a particular contact design have been specified. These gross features might be dictated by considerations other than optimized top-contact design such as the ease with which cells can be automatically interconnected. As a rule of thumb, the smaller the unit cell, the smaller the top-contact loss. Redundant contacts not only improve module reliability but also reduce top-contact losses by reducing the size of unit cells. If the sheet resistivity of the busbar is less than that of the fingers, it is best to use a design with long busbars and short fingers, as in the figure immediately preceding the Preface at the front of this book, provided that contact-resistance effects are small. In the case shown, the current-carrying section of the busbars

³This equation can be derived by differentiating the expression for the power loss ($p_{rf} + p_{cf} + p_{sf} + p_{tl}$) with respect to S . This derivative must equal zero for the optimum value of S . This optimum S is then found using the Newton iteration scheme (Ref. 8.7) for finding the roots of a nonlinear equation.

are the metal interconnect ribbons which extend the whole length of the cell. Even for rectangular cells, it may be worthwhile considering contact schemes other than the rectilinear ones discussed. For example, radial contact schemes such as illustrated in Fig. 8.12 can also give very low overall losses for rectangular cells.

It should be noted in passing that the equations described in this section are based on certain approximations (Ref. 8.8) regarding the size of the normalized power losses, the magnitude of resistive voltage drops, and the direction of current flow, particularly near intersections of fingers and busbars. Also, linear tapers may not be the optimum shape for busbars or fingers for differently shaped cells (Ref. 8.9). The effect of these second-order effects may be well worth checking for situations, such as in concentrating cells, where contact design is critical.

Problem: Design the top contact for a 10×10 cm silicon solar cell. This cell gives its maximum power output at a voltage of 450 mV and a current density of about 30 mA/cm². The sheet resistivity of the diffused layer in this cell is 40 $\Omega/\square$.

Two interconnections per cell are specified. The metallization is to be applied by plating and subsequent solder dipping. The finger width is specified as 150 μm . The sheet resistivity of the metallization is determined primarily by the solder layer, whose bulk resistivity is 15 $\mu\Omega\text{-cm}$. The solder builds up to an average thickness of 42 μm over the fingers and 80 μm over the wider busbars. The specific contact resistance between the fingers and the semiconductor is 370 $\mu\Omega\text{-cm}^2$.

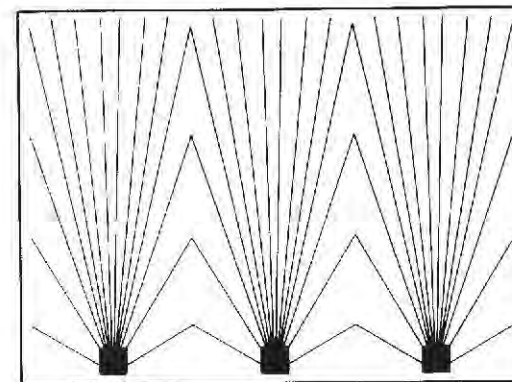


Figure 8.12. Radial contact metallization scheme for a rectangular cell.

Solution: In the terminology of this section,

$$J_{mp} = 0.03 \text{ A/cm}^2 \quad V_{mp} = 0.45 \text{ V}$$

$$\rho_s = 40 \text{ } \Omega/\square \quad \rho_c = 370 \text{ } \mu\Omega\text{-cm}^2$$

$$\text{Sheet resistivity of solder layers} = \frac{\text{bulk resistivity}}{\text{layer thickness}}$$

Therefore,

$$\rho_{smf} = 0.00357 \text{ } \Omega/\square \quad \rho_{smb} = 0.00188 \text{ } \Omega/\square$$

Since $\rho_{smb} < \rho_{smf}$, a contact design with long busbars and short fingers is preferable. One suitable for two interconnections per cell is shown in Fig. 8.13. This breaks down into four unit cells, each with $A = 10 \text{ cm}$, $B = 2.5 \text{ cm}$.

The optimized dimensions of the busbar can be calculated from Eq. (8.38). Using a tapered busbar ($m = 4$), its optimum width per unit cell is

$$W_B = 10 \times 2.5 \left(\frac{0.00188 \times 0.03}{4 \times 0.45} \right) \text{ cm} = 0.14 \text{ cm}$$

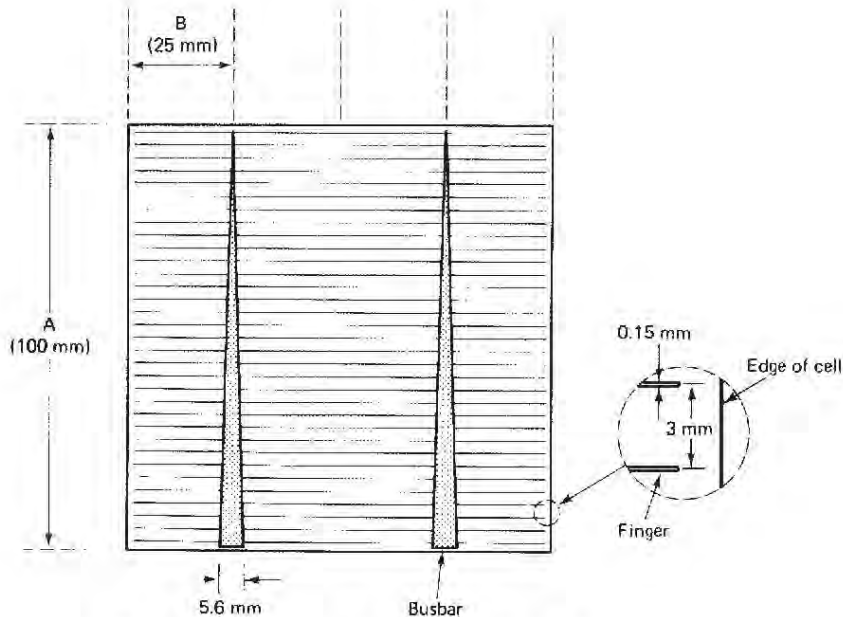


Figure 8.13. Contact scheme chosen for the design example. The shadowing loss is 10.6% and resistive losses in the contact and the diffused layer of the cell total 8.6%.

Since the actual busbar lies in two unit cells, the average busbar width is twice this. Hence, the busbar tapers from the thinnest value possible to a maximum width of 0.56 cm. The corresponding fractional power loss is, from Eq. (8.39),

$$p_{rb} + p_{sb} = 0.112$$

The finger width is specified as $150 \text{ } \mu\text{m}$ ($W_F = 0.015 \text{ cm}$). Assume that this is a result of technical limitations and the finger cannot be made any finer. With this constraint, a constant width ($m = 3$) finger will not be far below optimum. The optimum finger spacing S has to be found iteratively. A starting trial value is found by dividing the value given by Eq. (8.41) by 2. This gives

$$S = 0.3286 \text{ cm} \quad p_{rf} = 0.0109 \quad p_{cf} = 0.0005$$

$$p_{sf} = 0.0456 \quad p_{tl} = 0.0240$$

Substituting these values into Eq. (8.43) gives the improved trial solution:

$$S = 0.2962 \text{ cm} \quad p_{rf} = 0.0098 \quad p_{cf} = 0.0005$$

$$p_{sf} = 0.0506 \quad p_{tl} = 0.0195$$

Continuing this for another iteration gives

$$S = 0.2991 \text{ cm} \quad p_{rf} = 0.0099 \quad p_{cf} = 0.0005$$

$$p_{sf} = 0.0502 \quad p_{tl} = 0.0199$$

Further iteration does not change the value of S , indicating that an optimum has been reached. The total fractional power loss due to the fingers and the top layer resistance is 0.080. The combined losses in the cell for this contact design is then 19.2% of the intrinsic output. The complete contact design is specified in Fig. 8.13.

8.7 OPTICAL DESIGN

8.7.1 Antireflection Coating

The principle of a quarter-wavelength antireflection coating is illustrated in Fig. 8.14. Light reflected from the second interface arrives back at the first interface 180° out of phase with that reflected from the first interface, canceling it out to some extent.

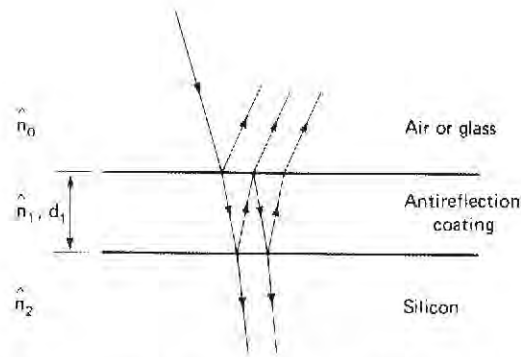


Figure 8.14. Interference effects created by a quarter-wavelength antireflection coating.

The expression for the fraction of the energy in a normally incident beam of light reflected from the surface of a material covered by a transparent layer of thickness d_1 is (Ref. 8.10)

$$R = \frac{r_1^2 + r_2^2 + 2r_1r_2 \cos 2\theta}{1 + r_1^2r_2^2 + 2r_1r_2 \cos 2\theta} \quad (8.44)$$

where r_1 and r_2 are given by

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1} \quad r_2 = \frac{n_1 - n_2}{n_1 + n_2} \quad (8.45)$$

where the n_i represent the refractive indices of the different layers. θ is given by

$$\theta = \frac{2\pi n_1 d_1}{\lambda} \quad (8.46)$$

When $n_1 d_1 = \lambda_0/4$, the reflectance has its minimum value:

$$R_{\min} = \left(\frac{n_1^2 - n_0 n_2}{n_1^2 + n_0 n_2} \right)^2 \quad (8.47)$$

This is zero if the refractive index of the antireflection (AR) coating is the geometric mean of those of the materials on either side ($n_1^2 = n_0 n_2$). For a silicon cell in air ($n_{si} \approx 3.8$), the optimum refractive index is the square root of that of silicon (i.e., $n_{opt} \approx 1.9$). Figure 8.15

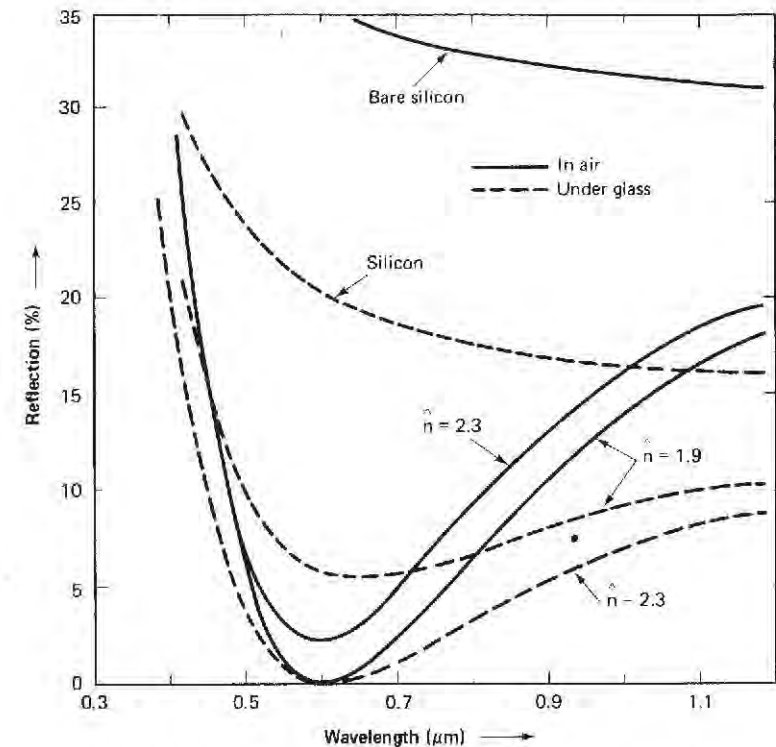


Figure 8.15. Percentage of normally incident light reflected from bare silicon and silicon with antireflection coatings of refractive indices of 1.9 and 2.3 as a function of wavelength. The thicknesses of the latter coatings are chosen to produce minimum reflection at 600 nm. The dashed lines show the effect of encapsulating the silicon under glass or material of a similar refractive index.

includes a curve showing the percentage of incident light reflected from silicon as a function of wavelength for an antireflection coating of this refractive index designed to produce minimum reflection at 600 nm. The weighted average of usable sunlight reflected from silicon can be kept to 10% as opposed to over 30% for bare silicon.

Cells are normally encapsulated under glass or embedded in a material of a similar refractive index to glass ($n_0 \sim 1.5$). This increases the optimum value of the index of the AR coating to about 2.3. Reflection from a cell with an AR coating of this refractive index is also shown in Fig. 8.15, both before and after encapsulation. The refractive index of a range of materials used in commercial solar cells is listed in Table 8.1. Apart from having the correct refractive index, the AR material must be transparent. It is usually deposited

Table 8.1. REFRACTIVE INDICES OF MATERIALS USED IN SINGLE- OR MULTIPLE-LAYER ANTIREFLECTION COATINGS

<i>Material</i>	<i>Refractive index</i>
MgF ₂	1.3-1.4
SiO ₂	1.4-1.5
Al ₂ O ₃	1.8-1.9
SiO	1.8-1.9
Si ₃ N ₄	~1.9
TiO ₂	~2.3
Ta ₂ O ₅	2.1-2.3
ZnS	2.3-2.4

as a noncrystalline or amorphous layer which prevents problems with light scattering at grain boundaries. Layers formed by vacuum evaporation generally tend to be absorbing at UV wavelengths. However, layers formed by such techniques as oxidizing or anodizing a deposited metal layer or layers deposited chemically tend to have a "vitreous" structure (amorphous with short-range order) which reduces this UV absorption (Ref. 8.11).

The use of multiple layers of AR coating materials can improve performance. The design of such coatings is more complex, but it is possible to reduce reflection over a broader band (Ref. 8.11). At least one manufacturer uses a two-layer coating in high efficiency cells to reduce the reflection of usable sunlight to 4%.

8.7.2 Textured Surfaces

Another approach previously mentioned to reduce reflection is to use textured surfaces. These are produced by etching the silicon surface with an etch that etches silicon much more rapidly in one direction through the crystal structure than another. This exposes certain planes within the crystal. The pyramids apparent in Fig. 7.6 are formed by the intersection of these crystal planes. In terms of Miller indices (Section 2.2), the silicon surface for textured cells is normally aligned parallel to a (100) plane and the pyramids are formed by the intersection of (111) planes. Dilute caustic soda (NaOH) solutions are a commonly used selective etch.

The angles of the pyramids are defined by the orientations of the crystal planes. These are such that incident light has at least two chances of being coupled into the cell. If 33% is reflected at each point of incidence, as is the case for normal incidence on bare silicon,

the total reflected overall is 0.33×0.33 , about 11%. If an antireflection coating is used, reflection of sunlight can be kept well below 3%. Even without an antireflection coating, the reflection when embedded in a material of refractive index similar to glass is only about 4%. Another desirable feature is that light is coupled into the silicon at an angle which ensures that it will be absorbed closer to the surface of the cell. This will increase the probability of its collection, particularly for the more weakly absorbed long wavelengths.

There are some disadvantages associated with the use of textured surfaces. One is that more care is required in handling (Ref. 8.12). A second is that such surfaces are much more effective in coupling light of all wavelengths into the cell, including unwanted infrared radiation of insufficient photon energy to create electron-hole pairs. This tends to make the cells "run hotter." Finally, top contact metallization has to run up and down the sides of the pyramids. If the height of the metal layer is less than or comparable to that of the pyramids ($\sim 10 \mu\text{m}$), it follows that two to three times the metal must be used to maintain the same resistive loss as on a flat surface.

8.8 SPECTRAL RESPONSE

The spectral response of a cell was mentioned in Section 5.5. It is the output current under short-circuit per unit incident power in monochromatic light as a function of wavelength. Measurement of the spectral response can provide detailed information about the design parameters of any particular solar cell.

Monochromatic light causes electron-hole pairs to be generated in the semiconductor with a spatial distribution given by

$$G = (1 - R) \alpha N e^{-\alpha x} \quad (8.48)$$

where N is the incident photon flux, R the fraction reflected, and α the absorption coefficient. For short wavelengths (UV light), α is large and light is absorbed quickly upon entering the semiconductor, as indicated in Fig. 8.16(a). Normal solar cells are not very effective at collecting light generated near the surface. If a quantum collection efficiency η_Q is defined as the number of electrons flowing in the external short-circuiting lead per incident photon in the monochromatic light, it will be very low for such UV light, as shown in Fig. 8.16(b). At intermediate wavelengths, α is smaller in value and a large proportion of the generated carriers are generated in regions where the collection probability is high. η_Q therefore increases.

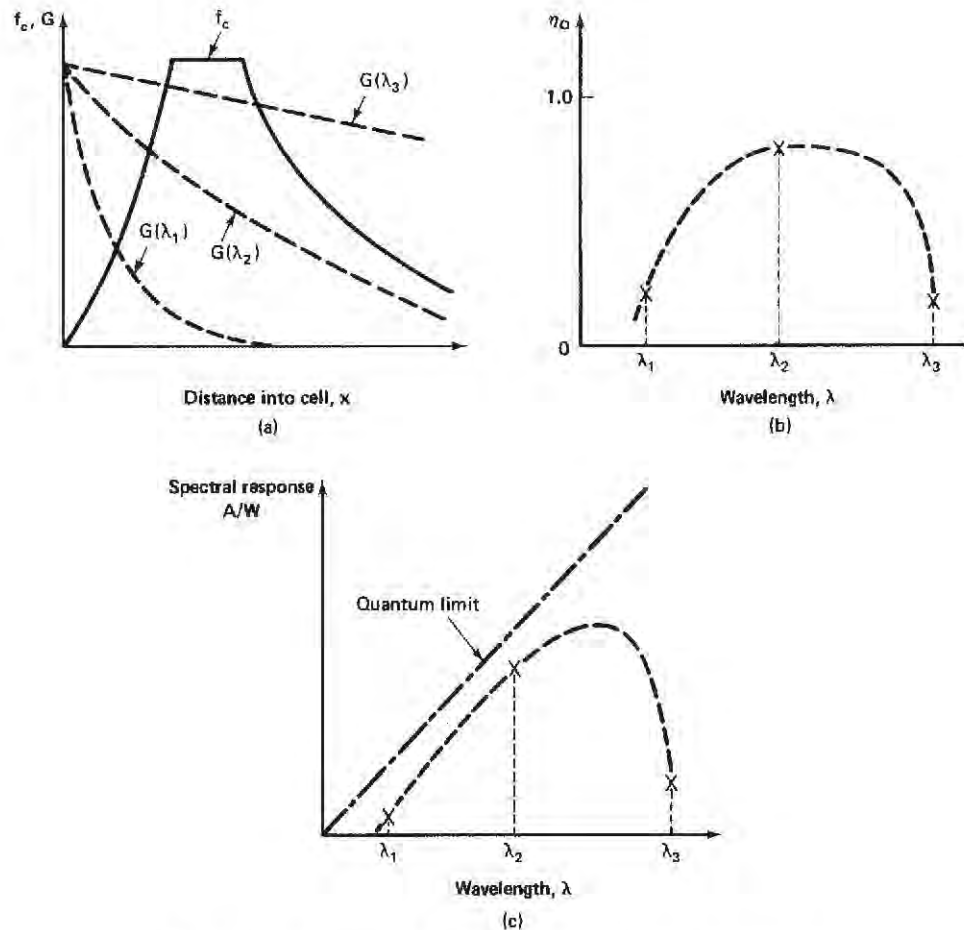


Figure 8.16. (a) Collection probability for a representative solar cell and, shown by the dashed lines, the carrier generation profiles for three different wavelengths of light. (b) Corresponding quantum collection efficiency, η_Q , as a function of wavelength. (c) Corresponding spectral sensitivity (A/W), also as a function of wavelength.

Long-wavelength light is absorbed very weakly and only a small proportion is absorbed in the active region of the cell. η_Q therefore decreases, dropping to zero once the photons have insufficient energy to create electron-hole pairs.

Another way of showing the spectral response apart from the quantum yield curve of Fig. 8.16(b) is to plot the sensitivity in A/W as a function of wavelength, as shown in Fig. 8.16(c). The quantum

limit is also indicated. At short wavelengths, the cells cannot utilize all the energy in the photons, so the sensitivity is low, even if operating ideally.

For “conventional” cells (referring to the type of cell developed for use in space), the response at short wavelengths is poor due to the deep junction employed augmented by the absorption in the AR coating. At long wavelengths, the spectral response is determined by the diffusion length in the cell material. The violet cell was a shallow junction cell developed in the early 1970s. The design emphasis was on achieving good collection at UV wavelengths by using the shallower junction and an improved, less absorbing AR coating. Textured cells demonstrate improved sensitivity to light at all wavelengths due to reduced reflection.

A back surface field (BSF) increases the collection probability for carriers generated near the back contact and hence boosts the long-wavelength sensitivity. The back contact to the cell can be designed to be reflective to give the longer wavelengths a second chance at being absorbed. Such back surface reflectors (BSR) can give quite a boost to the performance of thin cells, as well as helping to maintain low operating temperatures.

8.9 SUMMARY

The design of silicon junction solar cells has evolved from the following considerations. The p - n junction has to lie close to the surface of the cell to give maximum current output. This can lead to problems due to the lateral resistance of this layer unless it is doped as high as practical. Excessive doping of this layer introduces effects that cause its electronic properties to be less than optimal.

The optimum substrate resistivity for a solar cell depends on whether a back surface field is present. If absent, the optimum resistivity is quite clearly defined at dopant levels in the range 10^{16} to 10^{17} cm^{-3} . If present, the optimum becomes less dependent on resistivity and is displaced to lower dopant levels.

In the design of the top contact to the cell, the critical parameters determining the associated power loss are the contact layout, the sheet resistivities of the contact metal layer and the diffused top layer of the cell, and the minimum width line permissible with the technology used to define the contact geometry. A quarter-wavelength antireflection coating can increase the output current of a solar cell by 35 to 45%. Texturing the cell surface can produce even better performance, although there are some associated disadvantages.

EXERCISES

- 8.1. A particular silicon solar cell consists of a very thin, uniformly doped n -type layer on a p -type substrate. The surface recombination velocity along the surface of the n -type layer is very large. Assuming that minority-carrier diffusion lengths in the n -type layer are very large compared to the thickness of this layer, derive an expression for the probability of collection of minority carriers as a function of distance generated away from the surface in the n -type layer. (Note: Since the diffusion length is very large compared to the thickness of the n -type region, recombination in bulk of this region will be small and can be neglected compared to the rate of surface recombination.)
- 8.2. Calculate the sheet resistivity of the n -type layer in Exercise 8.1 given that the dopant concentration is 10^{18} cm^{-3} and the thickness of the layer is $0.5 \mu\text{m}$.
- 8.3. Silicon solar cells of conventional structure are fabricated on p -type wafers $150 \mu\text{m}$ thick. Cells with a high recombination back contact give a short-circuit current of 2.1 A and an open-circuit voltage of 560 mV . Similar cells with a back surface field give a short-circuit current of 2.2 A . Given that the minority carrier diffusion length in the p -type region after processing in all cases is $500 \mu\text{m}$, what would be the ideal value of the open-circuit voltage for the cells with a back surface field?
- 8.4. Design the top contact for a rectangular silicon solar cell $7.5 \times 10 \text{ cm}$ in size and calculate the total power loss of your design. The sheet resistivity of the diffused layer in this cell is nominally $60 \Omega/\square$. The cell gives its maximum power at a voltage of 430 mV and a current density of 28 mA/cm^2 under bright sunshine. Three interconnections per cell are specified, all lying along the same side of the cell.
- The metallization is to be applied by vacuum evaporation through a metal shadow mask. The minimum line width is specified as $180 \mu\text{m}$. The metallization consists of a layer of titanium ($0.12 \mu\text{m}$) adjacent to the silicon separated by a thin layer of palladium ($0.02 \mu\text{m}$) from a $4\text{-}\mu\text{m}$ -thick layer of silver. The specific contact resistance to the silicon is $200 \mu\Omega\text{-cm}^2$. The bulk resistivities of these metals are 48, 11, and $1.6 \mu\Omega\text{-cm}$, respectively.
- 8.5. Consider a cell of given top contact geometry with metallization and cell parameters fixed. Show that the relative power loss attributable to this top contact increases as the cell dimensions increase.

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Chapter 9

OTHER DEVICE STRUCTURES

9.1 INTRODUCTION

The basis for photovoltaic action in a semiconductor device is an electronic asymmetry in the device structure. There are, of course, a large number of ways of creating this asymmetry apart from using silicon p - n junctions as considered in previous chapters. In this chapter, several alternative device concepts are outlined.

9.2 HOMOJUNCTIONS

Conventional silicon solar cells are *homojunctions*. The semiconductor on either side of the junction is the same, differing only in dopant type. In Chapter 8, the normal cell structure with a shallow homojunction parallel to the illuminated surface was described. Rather than cataloging all the alternative homojunction possibilities, three specific devices are described in this section that illustrate several different homojunction concepts.

The first is the high-low emitter (HLE) structure of Fig. 9.1(a), which overcomes some of the limitations of the conventional approach. This device differs in that the p - n junction is much deeper and the doping density more moderate on the top side of the junction. A "front surface field" is used at the top of the device. This approach overcomes the limitations imposed on the open-circuit voltage by the diffused top layer of the normal cell structure. Substantial improvements in open-circuit voltage have been reported using this approach (Ref. 9.1). The probability of collection of generated carriers throughout the device is indicated in Fig. 9.1(b). Carrier collection is not optimum, so current outputs tend to be less than with other designs.

A second device structure is the front-surface-field cell shown in Fig. 9.2(a). With this approach (Ref. 9.2) it is possible to bring both contacts out the rear of the cell. This eliminates the shadowing losses associated with the normal top contact and would make cells easier to interconnect. However, the processing required is more complex. The cell also has to be thin compared to the minority-carrier diffusion length to get full current output, which could pose handling difficulties for large-area cells.

A third approach is to use junctions perpendicular to the illuminated surface of the cell, the vertical junction cell. The most practical implementation of this approach has been the vertical multijunction (VMJ) cell of Fig. 9.2(b). Deep grooves are etched into the cell using an anisotropic etch (Ref. 9.3) and the cell subsequently diffused to give a combination of horizontal and vertical junctions. These vertical junctions ensure that carriers generated deep in the cell can be

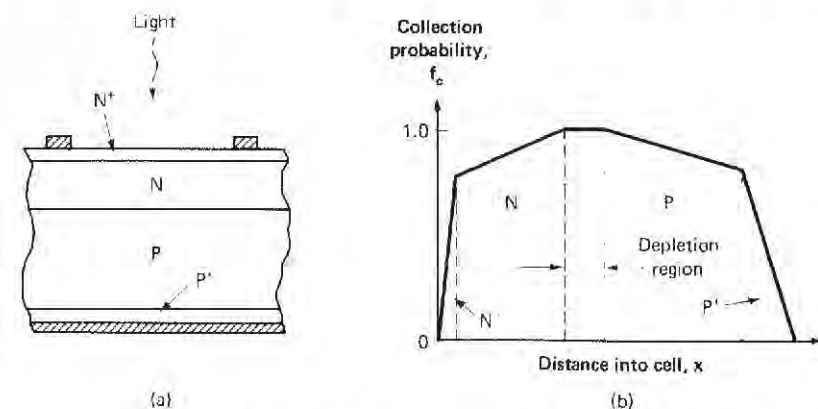


Figure 9.1. (a) Schematic diagram of the high-low emitter solar cell structure. (b) Corresponding collection probability as a function of distance from the surface of the cell.

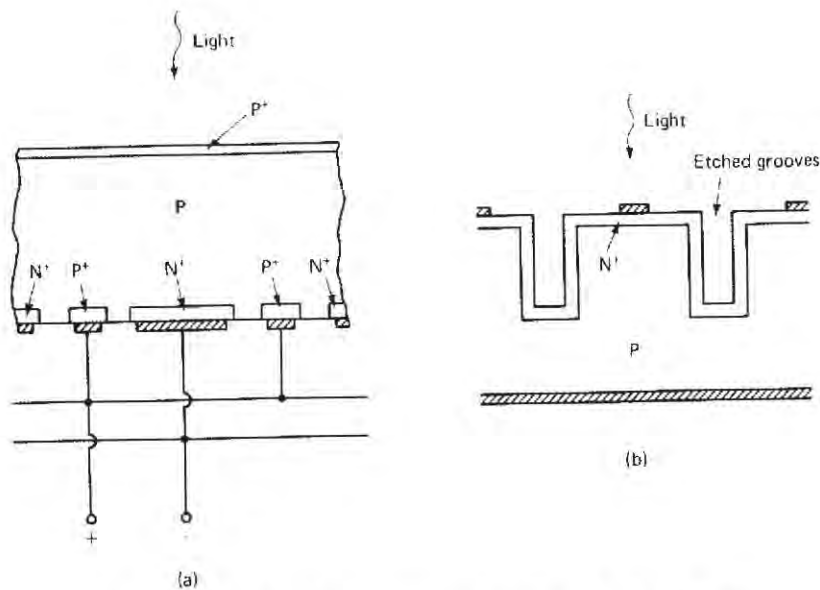


Figure 9.2. Other homojunction approaches to solar cell design:

- (a) Front surface field cell.
(b) Vertical multijunction cell.

collected. To be most effective, the vertical junctions must be of the order of a diffusion length apart. In principle such a structure is more tolerant of small diffusion lengths, although the smaller the diffusion length the finer the required physical dimensions of the structure.

9.3 SEMICONDUCTOR HETEROJUNCTIONS

In semiconductor heterojunctions, the materials on either side of the junction are semiconductors but *different semiconductors*.

In Section 4.2, the energy-band diagram for the homojunction case was derived by a conceptual experiment where isolated *p*-type and *n*-type regions were brought into contact. Repeating this approach for the heterojunction case, the band diagrams of the isolated pieces of semiconductor are shown in Fig. 9.3(a). Three parameters are of interest. These are the *work function* (energy required to remove an electron located at the Fermi level from the semiconductor), the *electron affinity* (energy required to remove an electron located at the energy of the conduction-band edge), and the *semiconductor band gap*.

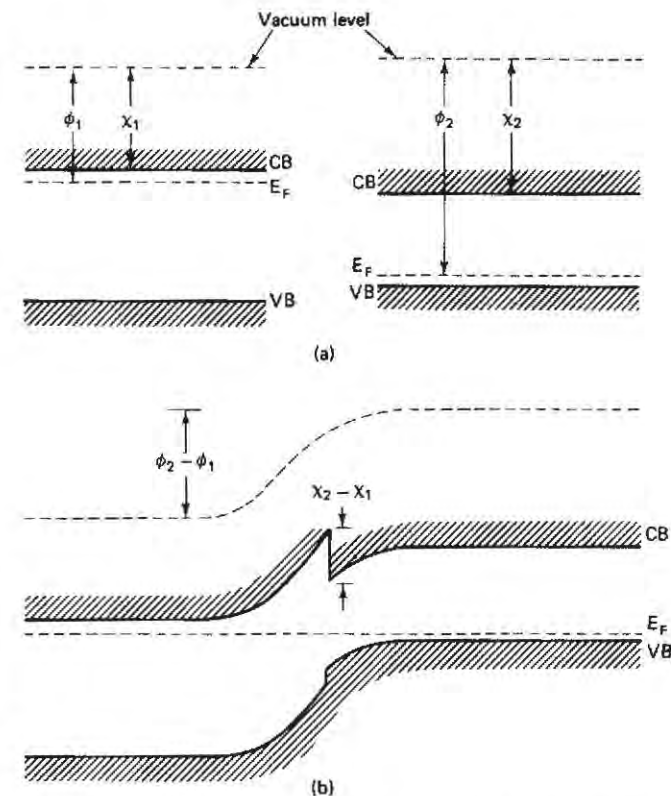


Figure 9.3. (a) Energy-band diagrams of isolated pieces of different semiconductors, one doped *p*-type, the other *n*-type. (b) Band diagram of the heterojunction formed by conceptually joining these pieces.

Not only are the doping levels different in the two isolated pieces, but the electron affinities, work functions, and band gaps are also different. When the two materials are joined together at thermal equilibrium, the Fermi level must be constant throughout the system, as indicated in Fig. 9.3(b). It follows that an electrostatic potential must build up across the device equal to the difference in work functions. The spatial distribution of this potential can be calculated in terms of charge stored in transition regions on either side of the junction in the same manner as in the homojunction case of Chapter 4. Additionally, there will be a discontinuity in the conduction-band edge at the junction equal to the difference in electron affinities and a corresponding discontinuity in the valence-band edge which also depends on the difference in band gaps. This is shown in Fig. 9.3(b). The *displacement*

vector ($e\xi$) will be continuous across ideal interfaces rather than the electric field as in the homojunction case.

Spikes in one of the bands as shown for the conduction band of Fig. 9.3(b) are undesirable for photovoltaic operation. Using the asymmetry concept of a solar cell as introduced in Section 4.1, the n -type region acts as a block for holes and the p -type as a block for electrons. A spike in the conduction band of the n -type region as in Fig. 9.3(b) also acts to block electron flow from the p -type to the n -type region. Hence, the spike will make it difficult for the p -type region to contribute to photocurrent. Such spikes can be avoided by a suitable combination of electron affinities and doping levels (Ref. 9.4).

For an ideal case with either small spikes or no spikes at all, the maximum efficiency of a heterojunction cell is bounded by the ideal efficiency of the smaller band-gap material. The reasons for considering heterojunctions are therefore practical reasons, rather than for fundamental efficiency advantages.

Up to the present point, nothing has been said about a very important practical consideration. For normal homojunctions, the same crystal structure continues right through the junction. For heterojunctions, this may not be possible because of gross differences in the crystal structure of the two semiconductors involved. From Fig. 9.4(a) it is apparent that for lattices of the same form but with a mismatch of lattice spacing, defects arise in the lattice structure. The

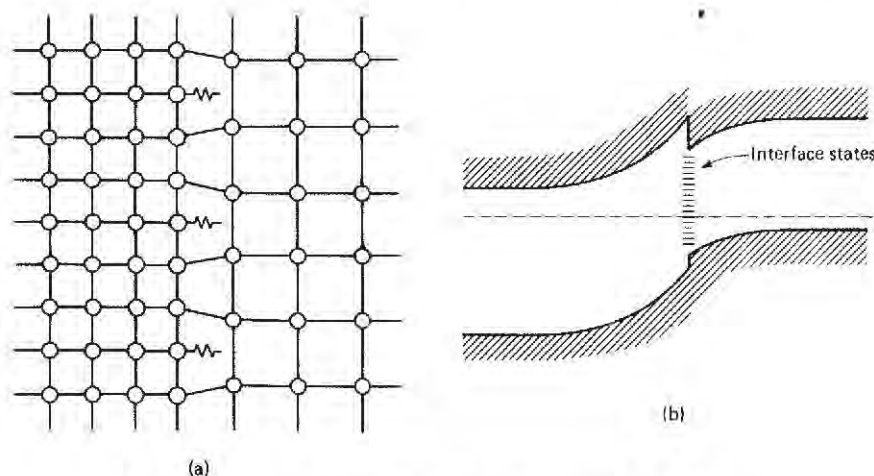


Figure 9.4. (a) Defects due to the mismatch at the interface between two lattices of different lattice constants. (b) Corresponding defect states in the forbidden gap caused by this mismatch.

density of defects depends on the degree of mismatch between the lattices. Defects in the crystal lattice give rise to allowed energy levels within the forbidden gap, as illustrated in Fig. 9.4(b). These allowed energy levels lie within the depletion region, where they act as very efficient recombination centers. They can also provide sites for quantum mechanical tunneling processes for current transport from one side of the junction to the other. In any case, they act to degrade the performance of the solar cell. To produce heterojunctions with nearly ideal properties, it is essential to use semiconductors with nearly identical lattice structures.

9.4 METAL-SEMICONDUCTOR HETEROJUNCTIONS

When a metal and semiconductor are brought into contact, a potential drop occurs in the interfacial region to account for work function differences, as in the case of semiconductor heterojunctions. Because of differences in the availability of charge carriers in the metal and semiconductor, essentially all this potential drop occurs on the semiconductor side of the junction, as indicated in Fig. 9.5(a). This can give rise to a depletion region at the interface as in the p - n junction case. The metal acts similarly to very heavily doped semiconductor material from the point of view of its effects on the electrostatic properties of the depletion layer.

Metal-semiconductor contacts with such depletion regions are known as *Schottky diodes*. They have both rectifying and photovoltaic properties. The situation for *minority carriers* in the semiconductor

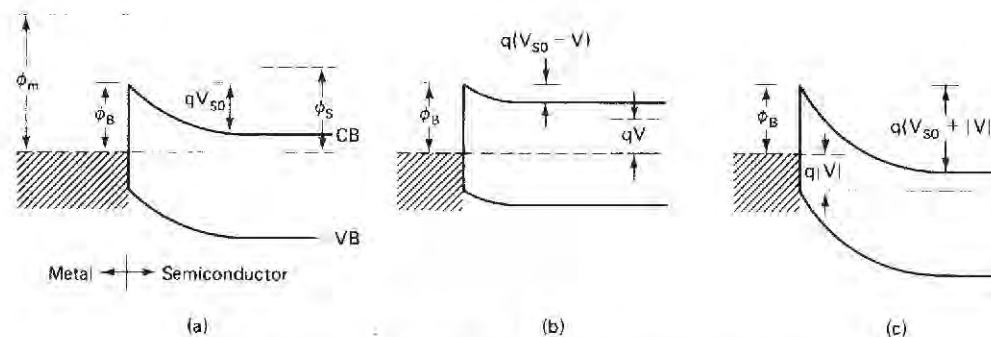


Figure 9.5. Energy-band diagram at a metal-semiconductor heterojunction:

- (a) Zero bias.
- (b) Forward bias.
- (c) Reverse bias.

region is essentially the same as for the case of a p - n diode. For example, in the dark the excess minority-carrier concentration at the edge of the depletion region depends exponentially on the applied voltage, with an exponential decay into the bulk (Section 4.4 and 4.6). Minority-carrier flows give a similar contribution to the total diode current. For n -type semiconductor

$$J_{0h} = \frac{qD_h n_i^2}{L_h N_D} (e^{qV/kT} - 1) \quad (9.1)$$

The only impediment to majority-carrier flow between the metal and the semiconductor is the depletion-region potential barrier at the interface. The height of this barrier varies with applied voltage as shown in Fig. 9.5(b) and (c). This gives rise to a *thermionic emission* component of current given by (Ref. 9.5)

$$J_{0e} = A^* T^2 e^{-q\phi_B/kT} (e^{qV/kT} - 1) \quad (9.2)$$

where A^* is the effective Richardson constant (~ 30 to 120 A/cm²/K²). The magnitude of this component depends primarily on the height of the barrier at the interface, ϕ_B . This majority-carrier component is normally much larger than the minority-carrier component of current, as indicated in Fig. 9.6(a). This extra component of current is *undesirable* from the point of view of photovoltaic energy conversion, because it acts to increase the dark saturation current of the diode and hence decrease the open-circuit voltage. This is indicated schemat-

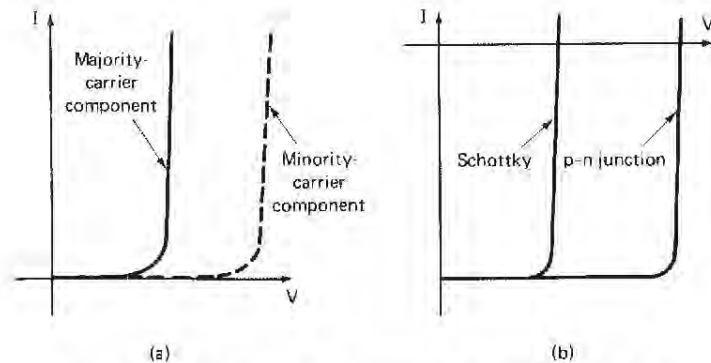


Figure 9.6. (a) Current components in a Schottky diode in the dark. (b) Comparison of the illuminated characteristics of Schottky and p - n junction devices.

ically in Fig. 9.6(b). Therefore, the larger the barrier ϕ_B , the better the performance.

It may seem an easy matter to select the metal work function in such a way as to induce a very large barrier at the metal-semiconductor interface to overcome this problem. However, it is found experimentally that, for many semiconductors, the size of the barrier induced is independent of the work function of the metal. This is attributed to a very large number of interface states at the metal-semiconductor interface due to lattice mismatch and possibly the effect of contaminants on the semiconductor surface (Ref. 9.6). These act to clamp the potential in the surface region.

Even though Schottky diodes can be made very simply because no p - n junction formation is involved, their performance is limited by the presence of the additional "parasitic" current component over and above those associated with p - n junctions.

9.5 PRACTICAL LOW-RESISTANCE CONTACTS

From Section 9.4, since the size of the barrier at the metal-semiconductor interface can seldom be controlled by selecting an appropriate metal, the question arises: How is it ever possible to make a nonrectifying or low-resistance contact between a metal and a semiconductor? The answer follows if the width of the depletion region associated with the rectifying contact is examined. As the doping density in the semiconductor increases, this width will decrease.

A metal to heavily doped semiconductor contact is shown in Fig. 9.7. The depletion region can become so thin that carriers can pass through classically forbidden regions by quantum mechanical tunneling processes (Ref. 9.7). Essentially, this is due to the wavelike

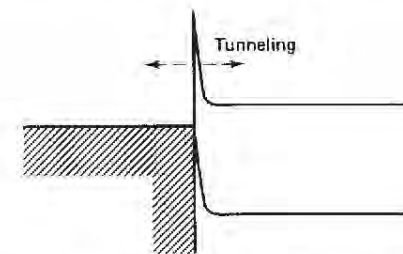


Figure 9.7. Contact between a metal and a heavily doped n -type semiconductor. The potential barrier in the latter regions is so thin that carriers can pass right through it by quantum mechanical tunneling processes.

nature of electrons which allows them to extend across such regions. Therefore, even though there is a barrier at the surface, carriers pass between the metal and semiconductor as if the thin barrier were not there. This gives a good low-resistance contact.

As a consequence, it is not difficult to make a good low-resistance contact to the heavily doped diffused layer of the cell. Electrical contact to the relatively lightly doped substrate region can be made by *alloying*, which leaves a heavily doped region near the interface. Alternatively, heavily damaged "as sawn" surfaces act sufficiently non-ideally to prevent rectifying action.

9.6 MIS SOLAR CELLS

It has been seen that metal-semiconductor contacts act nonideally for many semiconductors in that barriers at the interface are not as strongly dependent on the work function of the metal as expected from simple theoretical considerations. By inserting a thin insulating layer between the metal and the semiconductor as indicated in Fig. 9.8(a), this nonideality can be removed. In such metal-insulator-semiconductor (MIS) devices, extreme metal work functions can produce extreme effects in the semiconductor.

For example, for the *p*-type device of Fig. 9.8(b), a low metal work function will cause a very large barrier to be induced at the semiconductor surface. If the insulating layer is very thin, carriers will be able to flow through it by *quantum mechanical tunneling*. The current

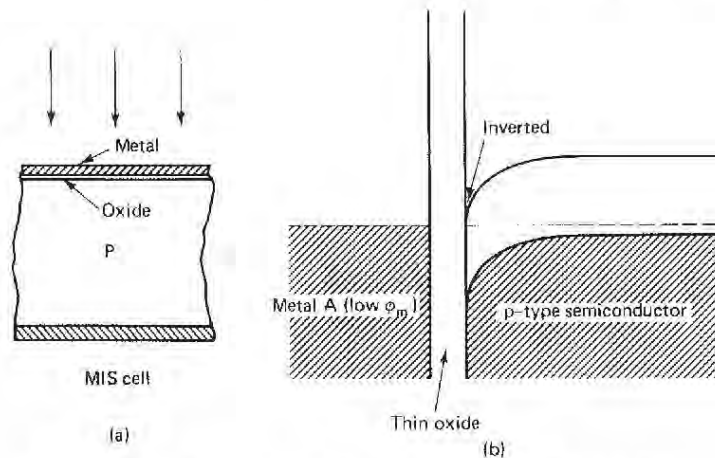


Figure 9.8. (a) Schematic of the metal-insulator-semiconductor structure. (b) Corresponding energy-band diagram.

that can flow through the insulator by this process increases exponentially with decreasing insulator thickness. The expression for the dark thermionic emission component of current given in Eq. (9.2) is then modified to

$$J_{0h} = P_h A^* T^2 e^{-q\phi_B/kT} (e^{q(V_{SO} - V_S)/kT} - 1) \quad (9.3)$$

where V_S is the potential at the semiconductor surface and V_{SO} is its value at thermal equilibrium. P_h is the probability the particle has of tunneling through. The presence of the thin insulator will also tend to reduce the maximum rate at which minority carriers can pass between the metal and semiconductor. However, provided that the thin insulator layer is not too thick (typically less than about 20 Å), transport of these carriers will be limited by their smaller transport rate through the semiconductor. In this case, the situation for minority carriers will remain the same as for the case of a *p-n* junction diode, and the corresponding dark current flow will be given by (Section 4.6)

$$J_{0e} = \frac{qD_e n_i^2}{L_e N_A} (e^{qV/kT} - 1) \quad (9.4)$$

Comparing the relative magnitudes of the two components of current flow for Schottky and MIS devices, the thermionic emission component of current can be suppressed in the latter by the fact that larger values of ϕ_B can be obtained, that the additional term P_h , the tunneling probability, can be very much smaller than unity, and that $(V_{SO} - V_S)$ in Eq. (9.3) may be smaller than the applied voltage V . From Fig. 9.6, such a suppression will increase the open-circuit voltage of the cell.

The ultimate situation is shown schematically in Fig. 9.9. In this case, the thermionic component of current has been suppressed to such low values that the *p-n* junction type of current flow given by Eq. (9.4) is left dominant. Hence, although structurally much different, MIS devices can be made electronically equivalent to ideal *p-n* junction diodes (Ref. 9.8).

In both Schottky and MIS solar cells, the top metal layer serves two functions, acting as both a contact and a barrier inducer. It is apparent from Fig. 9.8(a) that some way has to be found of getting the light through this layer. Two approaches are shown in Fig. 9.10. One is to use a metal layer thin enough (<100 Å) so that it is essentially transparent to light. This layer would have a high sheet resistivity, so a thicker contact grid would also be required as shown. A second approach is to use a grating structure essentially the same as the

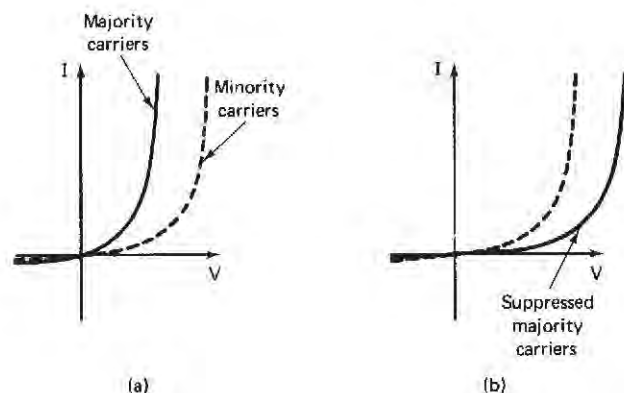


Figure 9.9. Comparison of the dark characteristics of (a) a Schottky and (b) an optimally designed MIS solar cell.

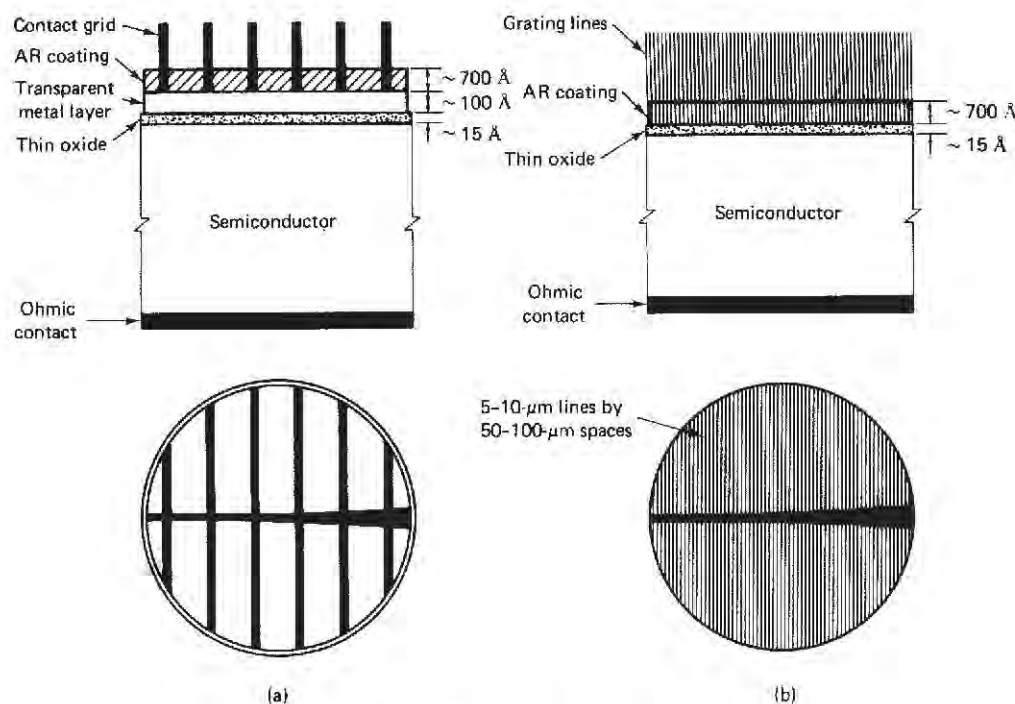


Figure 9.10. Two approaches to the design of the top contact of MIS solar cells:

- (a) Transparent metal approach.
- (b) Grating device.

top contact to conventional cells but very much finer. Carriers created by light absorbed between the grating lines have a good chance of reaching a nearby grating line before recombining. The situation can be further improved if it is possible to induce a layer of minority carriers along the surface electrostatically (Ref. 9.9). A third approach is to use a transparent conductor such as the oxides of tin, indium, zinc, or cadmium for the top contact. These conducting oxides are actually heavily doped semiconductors; hence, the resulting structure is known as the semiconductor-insulator-semiconductor (SIS) solar cell (Ref. 9.10). Such SIS devices are closely related to the semiconductor heterojunctions of Section 9.3.

The major advantage of the MIS approach is that the high-temperature junction diffusion step is completely eliminated. This allows the starting properties of the silicon material to be maintained as well as eliminating the nonidealities associated with the diffused layer. It was seen in Section 8.7 that these nonidealities place an upper limit on the open-circuit voltage of silicon cells. Using the grating MIS approach, very high open-circuit voltages have been reported for silicon solar cells (Ref. 9.8). Since current outputs are comparable and fill factors potentially higher, MIS cells have a potential efficiency advantage over diffused cells, owing primarily to this high output voltage.

9.7 PHOTOELECTROCHEMICAL CELLS

9.7.1 Semiconductor-Liquid Heterojunctions

If a semiconductor is brought into contact with an electrolyte, a potential barrier can be created at the surface of the semiconductor as for the other heterojunctions treated in this chapter. Minimal device processing is required to produce such semiconductor-liquid heterojunctions, which, nonetheless, have recorded energy-conversion efficiencies in excess of 12% (Ref. 9.11). The main problem with this approach has been the susceptibility of the semiconductor to photo-enhanced corrosion in this mode of operation (Ref. 9.12).

Combined with a conducting counter electrode, such "photo-electrical cells" can be used either to produce electricity or to produce hydrogen by the photoelectrolytic decomposition of water.

9.7.2 Electrochemical Photovoltaic Cells

In these devices, the liquid consists of a solution containing a species with an oxidized and a reduced state. If this species accepts an

electron, it changes from an oxidized to a reduced state. Conversely, giving up an electron or accepting a hole oxidizes it. Such species are known as a *redox couples*.

In an electrochemical photovoltaic cell, the energy level within the electrolyte of this redox couple ideally lies near the energy level of the minority-carrier-band edge at the semiconductor. This is illustrated in Fig. 9.11(a) for the case of *n*-type semiconductor with a metallic counter electrode.

Under illumination, minority carrier holes generated in the semiconductor move to the interface with the electrolyte. They are transferred across this interface as indicated in Fig. 9.11(a) to the reduced form of the redox couple, which they oxidize:



At the counter electrode, electrons are transferred from the metal to the oxidized form of the redox couple, which they reduce:



If a load is connected between the cell terminals, this will complete the electrical circuit and power will be supplied to it as in more conventional solar cells.

The electrolyte in these cells serves only to transfer charge between the metal and semiconductor. The device structure bears a

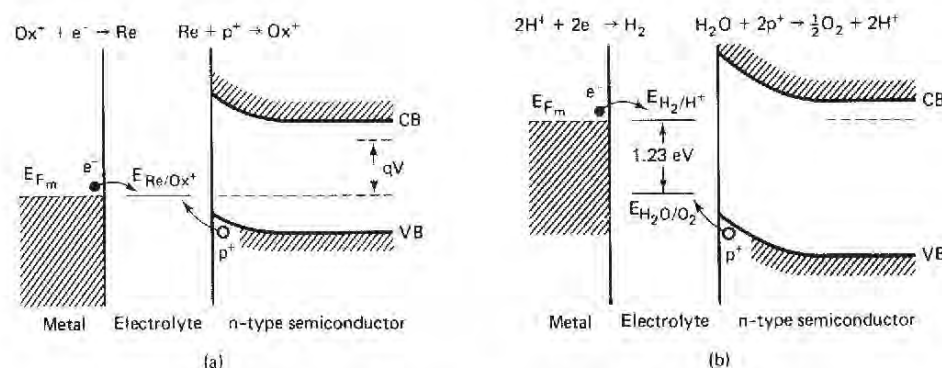


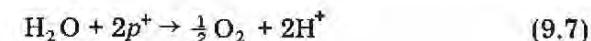
Figure 9.11. (a) Energy-band diagram of an electrochemical photovoltaic cell under illumination. The redox-couple level in the electrolyte allows charge transfer between the metal and the valence band in the semiconductor. (b) Energy-band diagram of a photoelectrolysis cell under illumination. Ideally, the device operates with the metal externally shorted to the rear of the semiconductor layer.

close relationship to the MIS structure of Section 9.6, as discussed further in Ref. 9.13.

9.7.3 Photoelectrolysis Cell

A cell very similar to the one described in Section 9.7.2 can also be used to produce chemical fuels by photoelectrolysis. The most common fuel produced has been hydrogen by the photoelectrolysis of water.

For an *n*-type semiconductor, reactions proceed as described in Section 9.7.2. An oxidation reaction occurs in the electrolyte near the semiconductor-electrolyte interface. A reduction reaction occurs near the counter electrode. The difference is that, unlike the case discussed in Section 9.7.2, the reacting species at each electrode are different. For the case of water decomposition, the reaction at the semiconductor electrode is (Ref. 9.14)



At the counter electrode,



The energy difference between the states associated with these reactions is 1.23 eV, as indicated in Fig. 9.11(b). This places a lower limit to the band gap of the semiconductor required for the reaction to proceed. All but semiconductors with much larger band gap than this have been found to corrode in this mode of operation (Ref. 9.12).

Titanium dioxide was the first semiconductor found to be stable in aqueous solution in this photoelectrolysis mode. However, it has a large band gap (3 eV) and so responds only to ultraviolet radiation. Solar-energy-conversion efficiencies are therefore low ($\sim 1\%$). In fact, this material absorbs so little sunlight that it is used as a "non-absorbing" antireflection coating on some commercial silicon cells! A small bias voltage (0.3 to 0.5 V) is required from an external power supply for this reaction to proceed for these TiO_2 devices. A material of smaller band gap with the required stability not requiring this bias is being sought.

9.8 SUMMARY

There is a wide range of photovoltaic device structural possibilities apart from the shallow homojunctions of previous chapters. Some

alternative device structures have been described in the present chapter. Heterojunctions between two different band-gap semiconductors have no intrinsic efficiency advantage over homojunctions. As will be seen in Chapter 10, there are often technological advantages. Metal-semiconductor heterojunctions can be fabricated very simply but are intrinsically less efficient than homojunctions, owing to an additional parasitic component of current. However, the use of a metal-insulator-semiconductor (MIS) heterojunction structure can reduce or even completely eliminate this deficiency.

Heterojunctions formed between liquids and semiconductors also possess interesting photovoltaic properties. In a photovoltaic mode of operation, laboratory cells can be fabricated very simply and have demonstrated reasonable efficiencies. In a photoelectrolysis mode, sunlight is converted directly into chemical energy, usually in the form of stored hydrogen. This combined energy collection and storage mode gives rise to interesting possibilities provided that energy-conversion efficiencies can be drastically improved over those reported in the past.

EXERCISES

- 9.1. (a) At room temperature, the dark saturation current density of homojunction cells made from material 1 is typically 10^{-8} A/m²; the corresponding figure for cells from material 2 is 10^{-11} A/m². Which of these materials would you expect to have the smaller band gap?
- (b) A p - n heterojunction is formed between these two materials. Assuming the absence of current-limiting spikes at the metallurgical junction and similar lattice structures so that there is little mismatch at this junction, estimate the dark saturation current density expected from this heterojunction. Which material is most important in determining the open-circuit voltage of the cell?
- (c) Which material will set the upper limit to the number of electron-hole pairs generated in the heterojunction and hence the short-circuit current?
- 9.2. (a) Find the ratio of the contributions made to the dark saturation current density of a Schottky diode solar cell by thermionic emission over the barrier at the metal-semiconductor interface and the diffusion of minority carriers through the semiconductor bulk at 300 K. The semiconductor is n -type silicon with the following parameters at 300 K: $N_D = 10^{22}$ m⁻³, $D_n = 0.001$ m²/s, $L_n = 10^{-4}$ m, and $n_i = 1.5 \times 10^{16}$ m⁻³. The barrier height at the interface is 0.8 eV and the effective Richardson constant is 10^6 A/m²/K².
- (b) If the cell gives a short-circuit current output of 300 A/m² under

bright sunshine (1 kW/m²), calculate the ideal value of the open-circuit voltage and cell efficiency.

- 9.3. A MIS cell is made with a structure similar to the Schottky cell of Exercise 9.2. Assume that the device achieves optimal performance by suppression of the magnitude of the thermionic emission component of current well below that due to the diffusion of minority carriers. Calculate the value of the open-circuit voltage and efficiency and compare to the results of Exercise 9.2.
- 9.4. Under bright sunshine (1 kW/m²), a photoelectrolysis cell based on titanium dioxide generates hydrogen at the diode surface. The cell requires a bias voltage of 0.4 V to operate and draws a current of 7 A/m² of cell area from the bias supply. The potential power which can be extracted from the hydrogen is $1.48I$, where I is the cell current and 1.48 is the voltage equivalent of the heat of combustion of hydrogen. What is the efficiency of conversion of sunlight for this cell?

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Chapter 10

OTHER SEMICONDUCTOR MATERIALS

10.1 INTRODUCTION

The semiconductor material that has been the focus of attention in earlier chapters has been single-crystal silicon. There is a wide range of other semiconductor material capable of producing solar cells of acceptable efficiencies (Ref. 10.1). No attempt is made in this chapter to catalog such material. Rather, the structure and properties of solar cells made on some of the more developed alternatives to single-crystal silicon are discussed. This will serve to indicate considerations of importance for more general materials.

10.2 POLYCRYSTALLINE SILICON

Techniques for preparing polycrystalline silicon are, in general, less critical than those required to produce single-crystal silicon. The purity of the starting silicon used to produce the polycrystalline material must still be similar to that used in single-crystal material to

get acceptable photovoltaic performance. But what other properties must polycrystalline silicon possess to produce reasonable solar cells?

The important regions in polycrystalline cells are the boundaries between the grains. An electrostatic barrier tends to develop on either side of the grain boundary (Ref. 10.2) similar to that developed in the metal-semiconductor heterojunction of Section 9.3. This tends to block majority carrier flows, acting essentially as a large series resistance. It makes the columnar grain structure of Fig. 10.1(b), where grains extend from front to back of the cell, more desirable than the case of Fig. 10.1(a), where they do not. Being defects in the crystal structure, grain boundaries introduce allowed levels into the forbidden gap of the semiconductor material and act as very effective recombination centers. As such, they may be considered as "sinks" for minority carriers. Just as minority carriers generated within a diffusion length of the junction of a solar cell are collected by the junction, so those generated within about the same distance of a grain boundary are attracted to the boundary and recombine. Such carriers do not contribute to the output current of the cell. As a consequence, it follows that the lateral dimensions of grains within polycrystalline material must be large compared to minority carrier diffusion lengths to avoid significant loss in current output (Ref. 10.3). Another deleterious effect that can be attributed to grain boundaries is their ability to provide shunting paths for current flow across the p - n junction. These conducting paths may develop from the preferential diffusion of dopants down grain boundaries during the junction formation step, as indicated in Fig. 10.1(c). A large density of precipitates at the grain boundaries would also be expected to contribute to these shunting paths.

Silicon, being a weakly absorbing indirect-band-gap semiconductor (Section 3.3.2), requires large diffusion lengths of the order of 0.1 mm for good photovoltaic performance. To avoid a signifi-

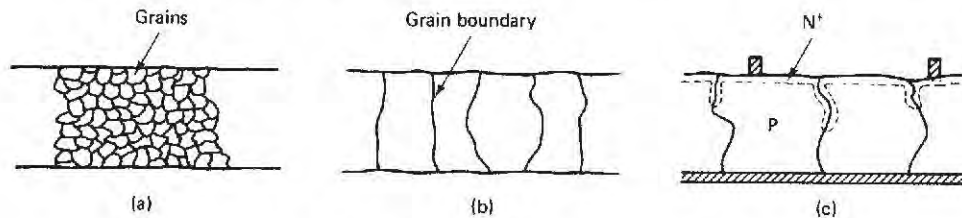


Figure 10.1. (a) Fine-grained polycrystalline material. (b) Polycrystalline material with columnar grains extending across the wafer thickness. (c) Preferential diffusion of dopant impurities down grain boundaries during cell processing.

cant loss of photocurrent due to recombination at grain boundaries, grains must have lateral dimensions much larger than this, of the order of a few millimeters. Since cells are normally only a fraction of a millimeter thick, such large grain size makes the columnar condition of Fig. 10.1(b) relatively easily satisfied. Moreover, the total length of grain boundaries per unit area of cell decreases as the grain size increases, decreasing the importance of shunting effects arising from these boundaries.

Such large grain sizes are much larger than those normally associated with polycrystalline material and the term *semicrystalline* is more appropriate. Figure 10.2 shows a wafer of such semicrystal-

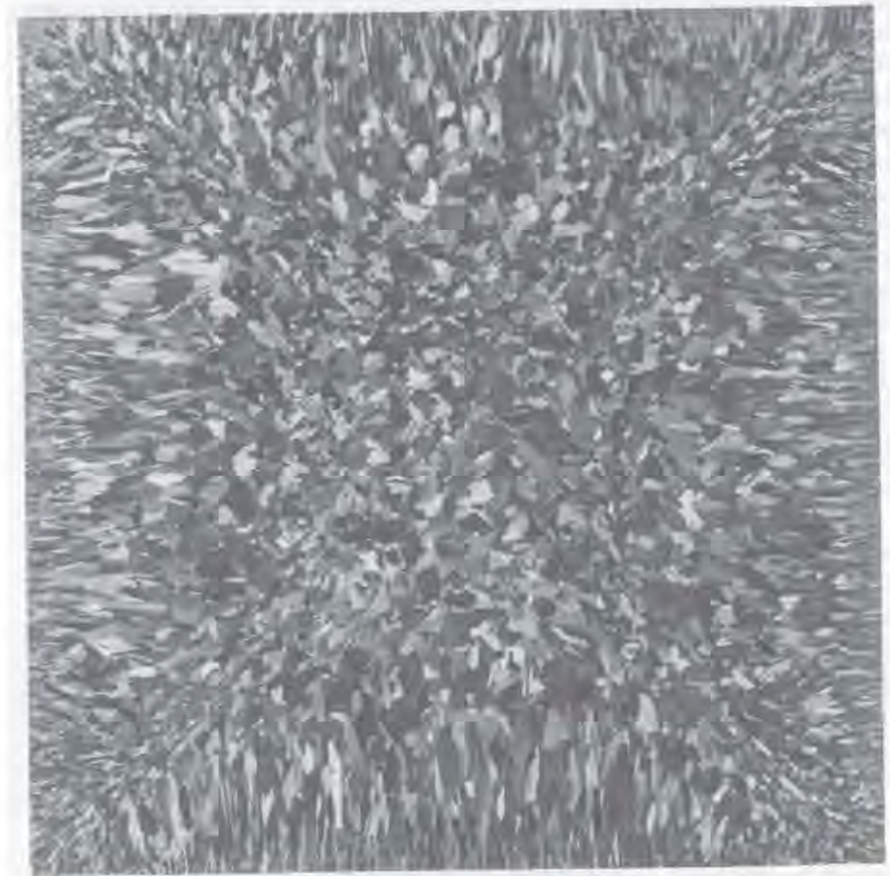


Figure 10.2. A 10 X 10 cm wafer of polycrystalline silicon sliced from an ingot formed by a casting process. Solar cells of 10% efficiency can be routinely produced on such wafers.

line silicon sliced from a cubic ingot of this material. In 1976, it was shown that solar cells of efficiencies in excess of 10% could be fabricated on such material (Ref. 10.4). Larger-grained material has since been reported to give efficiencies over 14% (Ref. 10.5). Solar modules based on such semicrystalline silicon are now available commercially.

10.3 AMORPHOUS SILICON

Conditions for preparing amorphous silicon are even less critical, in principle, than those for preparing polycrystalline silicon. An amorphous material differs from crystalline material in that there is no long-range order in the structural arrangement of the atoms. For example, silicon atoms in amorphous silicon will generally be connected to four other silicon atoms. The angles between the bonds joining these atoms as well as the bond lengths generally will be similar to those in crystalline material, but small deviations quickly result in a complete loss of long-range order.

Elemental amorphous silicon does not appear to possess any interesting photovoltaic properties in itself. Without the constraints of periodicity, it is difficult for each silicon atom to be linked up with four others. This gives rise to microvoids within the structure of the material with associated unsatisfied or "dangling" bonds. Combined with the nonperiodic arrangement of the atoms, this creates large densities of allowed states right across the normally forbidden band gap. These make it impossible to effectively "dope" the semiconductor or obtain reasonable carrier lifetimes.

However, it was reported in 1975 (Ref. 10.6) that amorphous silicon films produced by the glow discharge decomposition of silane (SiH_4) could be doped to form p - n junctions. These films contained hydrogen (created when the SiH_4 decomposes) as a reasonable proportion of the total atoms within the material (5 to 10%). It has been postulated that the role of hydrogen is to saturate dangling bonds on the internal microvoids of the film and at other defects in the structure as indicated in Fig. 10.3. This would reduce the density of states within the forbidden gap and allow the material to be doped.

Using amorphous silicon-hydrogen alloys (a-Si:H alloys) prepared in this way, a 5.5% efficient solar cell was reported in 1976 (Ref. 10.7). This was a very small area device based on a MIS structure, but it did bring attention to the possibilities of the approach. Much larger area p - n junction and MIS devices have since been fabricated with efficiencies approaching this value (Ref. 10.8). The a-Si:H

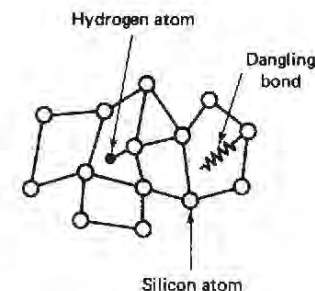


Figure 10.3. Schematic diagram of the structure of amorphous silicon, showing how dangling bonds arise and how these may be passivated by hydrogen.

alloys display significantly larger band gaps than crystalline silicon and also are much more strongly absorbing. This means that films of the order of $1\text{ }\mu\text{m}$ thick are all that are required. These films can be deposited onto a variety of substrates. Doping levels can be controlled by the presence of small quantities of gases containing the desired dopant during the deposition. Results indicate that minority carrier diffusion lengths in such material are very small, much less than $1\text{ }\mu\text{m}$. As a consequence, the depletion region forms most of the active carrier collecting volume of the cell. Series resistance of the bulk regions of the cells tends to be a problem. However, reduction of this resistance when the cell is illuminated (*photoconductive effect*) compensates to some extent.

Since the cells are so easily deposited, it is not difficult to form several interconnected cells on the one substrate. This has the advantage that the size of any individual cell can be kept small, eliminating the requirement for a metal contact grid (Ref. 10.9). The first commercial products based on amorphous silicon appeared in 1980. These utilized small cells interconnected on the one substrate as shown in Fig. 10.4(a). These produce the required voltage and current to power the consumer products indicated in Fig. 10.4(b). These cells were over 3% efficient in sunlight but *matched the performance of single-crystal silicon cells in indoor fluorescent lighting*. The search is under way in research laboratories around the world to find a material based on amorphous silicon which will repeat this feat outdoors.

A development in this area is the use of amorphous silicon layers with both hydrogen and fluorine incorporated into the structure (Ref. 10.10). These a-Si:F:H alloys have been produced by the glow discharge decomposition of SiF_4 in the presence of hydrogen. This approach has been reported to lead to more desirable



Figure 10.4. (a) First commercial amorphous silicon solar cell arrays designed for use in consumer products. (b) Calculator and watches powered by these arrays. (Photographs courtesy of Sanyo Electric Co. Ltd.)

except that every second atom is different (either Ga or As). GaAs is also a direct-band-gap semiconductor (Section 3.3.1). This means that sunlight is absorbed very quickly after entering it. It also means that minority carrier lifetimes and diffusion lengths are much smaller than in silicon. These differences result in different cell design concepts.

GaAs has a well-developed technology because of the commercial interest in this material for light-emitting diodes and semiconductor injection lasers. One aspect of this technology has been the utilization of alloys of GaAs and AlAs. The latter material is an indirect-band-gap semiconductor ($E_g \approx 2.2$ eV) with a lattice structure similar to GaAs, with the lattice spacing nearly identical (only 0.14% mismatch). Alloys of GaAs and AlAs, normally written $\text{Ga}_{1-x}\text{Al}_x\text{As}$, have a lattice spacing and band gap intermediate between GaAs and AlAs. Because of the good match of lattice spacing, heterojunctions between GaAs, AlAs, and their alloys can have low densities of interfacial states and, as a consequence, nearly ideal properties. This adds an additional degree of flexibility to the design of photovoltaic devices.

Because of its nearly ideal band gap (Fig. 5.2) and its developed technology, the most efficient solar cells ever reported have been based on GaAs. Terrestrial efficiencies of over 22% have been reported under AM1 sunlight, substantially higher than the corresponding figure of 18% for silicon. However, there are some disadvantages with the use of GaAs as a solar cell material. The limited resources of gallium (Ref. 10.11) will ensure that GaAs is always an expensive material. This is offset by the fact that GaAs cells are ideal for use in systems that concentrate sunlight (Chapter 11). The amount of material required for a given power output is reduced as a consequence. The direct band gap of GaAs also means that light is absorbed very quickly after entering this material. Therefore, layers only a few microns thick are all that are required, further reducing material requirements. A second disadvantage is the toxic nature of arsenic. The environmental consequences of deploying large solar systems based on toxic materials would have to be carefully examined (Ref. 10.12).

10.4 GALLIUM ARSENIDE SOLAR CELLS

10.4.1 Properties of GaAs

Gallium arsenide (GaAs) is an example of a *compound semiconductor*. It has a similar crystalline structure to silicon (Fig. 2.3)

10.4.2 GaAs Homojunctions

Because light is absorbed very quickly upon entering a direct-band-gap semiconductor such as GaAs, problems with high surface-recombination velocities are even more serious for the conventional

homojunction structure than for the case of silicon. Prior to 1978, efficiencies reported for GaAs homojunctions had been moderate.

The technique used for reducing surface-recombination effects for silicon was to make the top layer of the homojunction thin compared to the average depth where photons are absorbed (Section 6.2.2). The same technique also works for GaAs, although in this case, the layer has to be an order of magnitude thinner. Efficiencies in excess of 20% have been reported for an N^+PP^+ solar cell structure of Fig. 10.5(a) in which the top N^+ layer was only 450 Å thick (Ref. 10.13).

For fabricating cells based on GaAs, there is an emphasis on different processing techniques than those described for conventional silicon cells. Rather than forming doped layers by diffusing impurities into the GaAs, the more common technique is to chemically build up layers incorporating the required dopant density. These layers added to the device continue the crystal structure of the underlying substrate and are known as *epitaxial layers*. They are formed by heating the substrate in the presence of chemicals in either the vapor or the liquid phase which contain the materials it is desired to deposit.

The structure of Fig. 10.5(a) can be formed by starting with a heavily doped P^+ substrate, epitaxially growing a more lightly doped P layer of a few microns and then growing a thin heavily doped N^+ layer. Anodic oxidation of some of this layer to form the antireflection coating helps keep the recombination velocity at the surface of this layer to a minimum (Ref. 10.13).

10.4.3 $Ga_{1-x}Al_xAs/GaAs$ Heteroface Cells

An alternative technique used to overcome the limitations of high surface-recombination velocities for direct-band-gap GaAs is to use the *heteroface* structure of Fig. 10.5(b). Because of the nearly identical structure of GaAs and alloys with AlAs, it is possible to build up an epitaxial layer of $Ga_{1-x}Al_xAs$ on the surface of a homojunction cell. If the parameter, x , is about 0.8, this layer will have a large indirect band gap. There will be little absorption of sunlight in passing through such a layer. In essence, it will act as a "window layer," allowing light through to the underlying cell as indicated in Fig. 10.5(d). Since the good lattice match to the substrate causes few interface states at the heteroface junction, the window layer also passivates the surface of the underlying GaAs.

This device structure has resulted in the best single cell efficiencies yet reported, with values in excess of 22% in terrestrial sun-

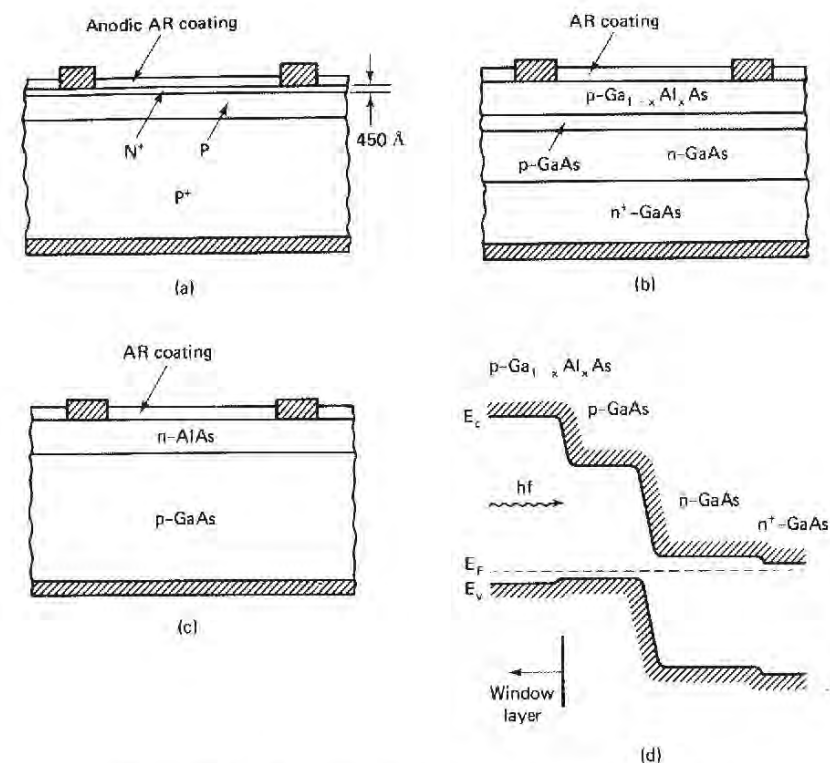


Figure 10.5. Schematic diagrams of different approaches to the design of GaAs solar cells:

- (a) GaAs homojunction.
- (b) $Ga_{1-x}Al_xAs/GaAs$ heteroface cell.
- (c) AlAs/GaAs heterojunction.
- (d) Energy-band diagram corresponding to the heteroface cell shown in part (b).

light (Ref. 10.14). The processing sequence is to start with an n -type substrate of GaAs and epitaxially grow the overlying p -type $Ga_{1-x}Al_xAs$ layer from the liquid phase. The same processing step also dopes the top portion of the substrate p -type by the diffusion of p -type impurities. Obtaining reliable low-resistance contacts to the $Ga_{1-x}Al_xAs$ layer can present difficulties that will be particularly important for cells to be used in concentrated sunlight. This problem can be avoided either by etching through this layer in the contact area and making contact to the underlying p -type GaAs (Ref. 10.15) or by building up a heavily doped p -type GaAs layer on top of it in the contact area (Ref. 10.16).

10.4.4 AlAs/GaAs Heterojunctions

Efficiencies in excess of 18% have also been obtained with a “true” heterojunction between *n*-type AlAs and *p*-type GaAs (Ref. 10.17) as shown in Fig. 10.5(c). The large indirect band gap of AlAs causes it to act as a window layer, allowing most of the light to be absorbed well into the bulk of the solar cell. The mismatch in the electron affinities of AlAs and GaAs causes a spike in the conduction-band energy of the heterojunction (Section 9.3). By having the AlAs heavily doped, the undesirable effects of this spike can be minimized (Ref. 10.17).

10.5 Cu₂S/CdS SOLAR CELLS

10.5.1 Cell Structure

CdS cells have a history of development dating back to 1954 (Ref. 10.18), about the same year as the first results appeared for diffused silicon cells. Since then there have been several attempts to produce a commercial solar cell based on this material.

The striking feature of these cells is the ease with which they can be fabricated. Because fine-grained polycrystalline CdS is adequate as a substrate material, this opens up a large number of ways of preparing such substrates. Vacuum evaporation and spraying methods seem the most promising.

CdS cells are normally made by a process known as the *Clevite process*. CdS is vacuum-evaporated onto a metal sheet or a metal-covered plastic or glass sheet. The CdS has to be deposited to a thickness of only 20 μm or so. The diameter of the crystallites in this layer may be approximately 5 μm . The layer is then dipped in a cuprous chloride solution (80 to 100°C) for 10 to 30 s. This substitutes Cu for Cd in a thin surface region about 1000 to 3000 Å thick, giving a Cu₂S/CdS heterojunction. A grid contact is then deposited. Figure 10.6(a) shows the completed cell structure. The Cu₂S layer can extend several microns down grain boundaries, as shown. A diagram showing the energy-band relationships is given in Fig. 10.6(b). The Cu₂S material is *p*-type with a band gap of 1.2 eV, whereas the CdS is *n*-type with a gap of 2.3 eV.

Efficiencies of cells produced in this way have been in excess of 9% (Ref. 10.19), with about 5% obtainable in pilot production.

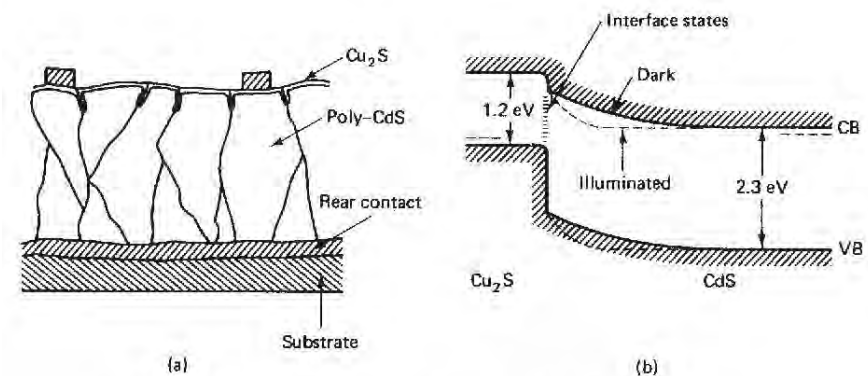


Figure 10.6. (a) Schematic diagram of the Cu₂S/CdS thin-film solar cell. (b) Corresponding energy-band diagram in the dark and when illuminated.

10.5.2 Operating Characteristics

Cu₂S/CdS cells perform almost anomalously well considering their inherent simplicity. However, the mechanisms responsible for their good performance are not nearly as well characterized as for Si or GaAs cells. Their operation can be described only by introducing concepts additional to those described in connection with the latter cell types.

The response of Cu₂S/CdS cells involves several nonlinearities. The most obvious demonstration of this is the fact that their current-voltage characteristics under illumination can cross over their dark characteristics, as demonstrated in Fig. 10.7(a). In addition, the open-circuit voltage of these cells and their fill factors depend on the spectral content of the light source, not just the light-generated current density, as also shown in Fig. 10.7(a). The cell capacitance also increases by a large factor (in the range 10 to 100) when the cells are illuminated. The spectral response of the cells shown in Fig. 10.7(b) also depends strongly on the intensity (and also the spectral composition) of the bias light. Although all the foregoing effects are generally observed, their magnitudes vary widely with different fabrication conditions.

The capacitance results indicate that the width of the depletion region contracts under illumination as illustrated in Fig. 10.6(b). A possible explanation of this (Ref. 10.20) is that trapping levels are created in the area of the depletion region by copper impurities which diffuse into this region during the formation of the Cu₂S layer

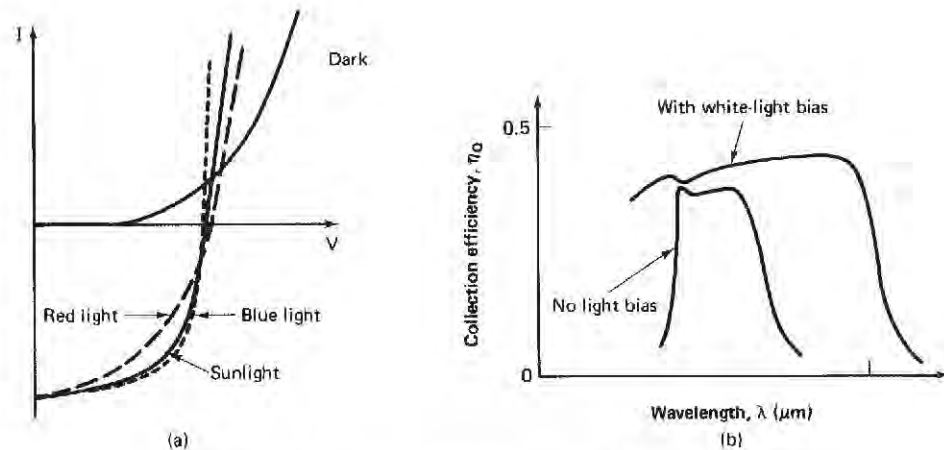


Figure 10.7. Nonlinearities associated with Cu₂S/CdS solar cell operation:

- (a) Crossover of dark and illuminated curves and dependence upon the spectral content of the illumination.
- (b) Enhancement of the spectral response by the application of bias light. (After Ref. 10.20, © 1978 IEEE.)

or subsequent heat treatment. Under illumination light-generated holes may be trapped in these levels. This would act to augment the positive charge due to donor impurities in this n -type region and hence decrease the depletion-layer width, as described mathematically in Eq. (4.4). This would also increase the value of the electric field strength in this region, as also indicated by Eq. (4.4).

This also allows the spectral response of the cells to be explained. There is likely to be a large number of allowed states in the forbidden gap at the Cu₂S/CdS interface due to lattice mismatch. These are indicated in Fig. 10.6(b). They act as efficient recombination centers. However, it is possible to show that the efficiency of such recombination centers decreases in the presence of large fields. Carriers are swept past these centers in such cases so rapidly that the probability of recombination is decreased. Most of the light-generated current comes from the thin Cu₂S top layer with its 1.2-eV band gap. Relatively little comes from the wider-band-gap (2.3 eV) CdS layer (Ref. 10.21). With no bias light, fields at the interface are relatively small, so that collected carriers have a good chance of recombining and the spectral response of the cells is poor, as shown in Fig. 10.7(b). With bias light, fields become large, recombination decreases, and the spectral response improves.

The sensitivity of the characteristics to different wavelengths

of light can then be related to the relative ability of different wavelengths to cause traps near the interface to be occupied by holes. However, the explanation given above is only one of many possible explanations of the characteristics, and even if it were largely correct, additional mechanisms would be required to be incorporated into it to describe all the observed experimental features.

10.5.3 Advantages and Disadvantages of Cu₂S/CdS Cells

The prime advantage of Cu₂S/CdS cells is the ease with which they can be fabricated on a variety of supporting substrates, making the cells extremely well suited for large-scale automated production. The cells themselves can be produced very inexpensively.

The major disadvantages of these cells are their low efficiency and their lack of the inherent stability possessed by silicon cells. With low efficiencies, the costs of other parts of a system become more important because the area of solar cells required for a given output increases. Balance-of-system costs, such as those due to site preparation, support structures, and wiring, can dominate system costs to such an extent that even if the cells were free, it would be cheaper to use higher-efficiency cells of higher cost. As a rule of thumb, 10% module efficiency is the lowest that can probably be tolerated for cost-effective large-scale generation of photovoltaic power.

The same consideration applies to the encapsulation costs of the cells. This is compounded by the fact that Cu₂S/CdS cells are inherently less stable than other cell types that have been developed and hence require more careful encapsulation if they are to have comparable operating life.

A number of degradation modes have been demonstrated by CdS cells (Ref. 10.22): (1) under high humidity, (2) at high temperatures ($>60^\circ\text{C}$) in air, (3) when illuminated at high temperatures, and (4) when the load voltage exceeds 0.33 V.

Moisture absorbed in the cell creates additional traps which act to decrease the short-circuit current. This is a reversible process, and the original current can be retained with appropriate heat treatment. If the devices are heated above 60°C in air, irreversible changes in this current can occur, attributed to conversion of the Cu₂S to mixtures of CuO and Cu₂O by reaction with oxygen and moisture. Even if air is not present, illumination at such temperatures can decrease the efficiency. This is attributed to a light-activated phase change in the Cu₂S layer, where some is converted to Cu_xS with

$x < 2$. This change in stoichiometry lowers the efficiency considerably. Operation of the cells at voltages in excess of 0.33 V can cause a light-activated change of Cu_2S to CuS and Cu . The Cu can form fine filaments, effectively shunting the junction.

It is maintained that these degradation modes can be eliminated by minor changes in the cell fabrication method and by hermetic encapsulation of the cells. From the point of view of the widespread application of photovoltaics, the CdS technology suffers from the less-than-infinite reserves and the toxicity of Cd .

10.6 SUMMARY

There is a large range of materials that may prove viable alternatives to the single-crystal silicon which forms the basis of the present solar cell industry. Some of the more developed of these have been described in this chapter.

Gallium arsenide is a semiconductor with a well-developed technology and a nearly ideal band gap for solar photovoltaic energy conversion. The most efficient solar cells made to date have been based on this material. Homojunction, heteroface, and heterojunction cells have all been shown capable of high efficiency, overcoming the more severe constraints of surface-recombination velocity in direct-band-gap material. The high cost of this material is its major limitation.

Copper sulfide-cadmium sulfide cells can be fabricated very simply on small-grained polycrystalline cadmium sulfide. Although potentially a very low cost technology, the difficulty of achieving 10% efficiency on a production basis combined with stringent encapsulation requirements to prevent degradation may prevent its widespread use.

Polycrystalline silicon has the disadvantage that large grain sizes are required. This eliminates many low-cost preparation methods. Even with large-grained semicrystalline material, there are some advantages over single-crystal silicon which have resulted in commercial cells based on such technology. The most promising silicon thin-film technology is that based on amorphous silicon alloys. Very rapid laboratory and commercial progress has been made with this technology since its desirable features were identified.

EXERCISES

- 10.1. A thin layer of polycrystalline silicon is deposited on a supporting metallic substrate. The grains in this layer have the columnar structure of Fig.

10.1(b), with the lateral dimensions of the grains equal to the layer thickness. A p - n junction is formed close to the surface of this layer with negligible preferential diffusion of dopants down grain boundaries. Assume that the grain boundaries act as infinitely large sinks for minority carriers and that the recombination velocity at the metal-semiconductor interface at the rear of the cell is also very large. Approximating each grain as a cube, calculate the maximum probability that a minority carrier generated right at the center of the volume defined by a grain has of contributing to the short-circuit current of the cell. (Note: Under short-circuit, the p - n junction is a very attractive region for minority carriers acting as another sink. The maximum collection probability will occur when the minority carrier diffusion length is much larger than the grain dimensions. This corresponds to the case where no recombination occurs within the internal volume of the grain.)

- 10.2. For the heteroface solar cell of Fig. 10.5(b), sketch the form of the rate of generation of electron-hole pairs as a function of distance beneath the cell surface.
- 10.3. A certain technology produces 10% efficient solar modules at a cost of \$1 per peak watt output under bright sunshine (1 kW/m^2). In a particular application, those balance-of-system costs that depend on the area of the array deployed amount to \$80 per m^2 . Assuming that other costs are identical in each case, at what price would 5% efficient modules produced by a second technology have to sell to give similar overall system costs?

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CONCENTRATING SYSTEMS

11.1 INTRODUCTION

One possible approach to reducing the cost of photovoltaic power even with present cell technology is to reduce the area of cell required for a given power output by concentrating the sunlight. In this way the cost of the system can be displaced from the cells to the cost of the concentrating elements and sun tracking system if required.

In general, the higher the concentration ratio, the smaller is the range of angles of light rays that the system will accept. Once the concentration ratio becomes greater than about 10, the system can utilize direct sunlight only and must track the sun in its path across the sky. The higher the concentration ratio, the more accurately the sun must be tracked. The finite range of angles reaching the earth from the sun due to its finite size determines the maximum possible concentration ratio (about 45,000).

Concentrating the sunlight on a cell will also tend to increase its operating temperature, which will decrease its efficiency. Passive

cooling (fins, etc.) is adequate for concentration ratios up to about 50. Active cooling is required for higher concentration ratios. *Total energy systems* which use both the photovoltaic energy and the thermal energy collected by the cooling system are entirely feasible.

11.2 IDEAL CONCENTRATORS

The geometrical concentration ratio, C , is defined as the ratio of the aperture area of the system to the active cell area. As mentioned previously, this ratio is closely related to the range of angles, θ_m , which the concentrating system can accept. From thermodynamic arguments it is possible to derive relationships between the maximum possible concentration ratio and the acceptance angle. For systems that concentrate light arriving at different angles within the range of acceptance angles by an equal amount, the maximum concentration ratio is given by (Ref. 11.1)

$$C_{m(2D)} = \frac{1}{\sin(\theta_m/2)} \quad (11.1)$$

for a *two-dimensional or linear concentrator* as indicated in Fig. 11.1(a), and

$$C_{m(3D)} = \frac{1}{\sin^2(\theta_m/2)} \quad (11.2)$$

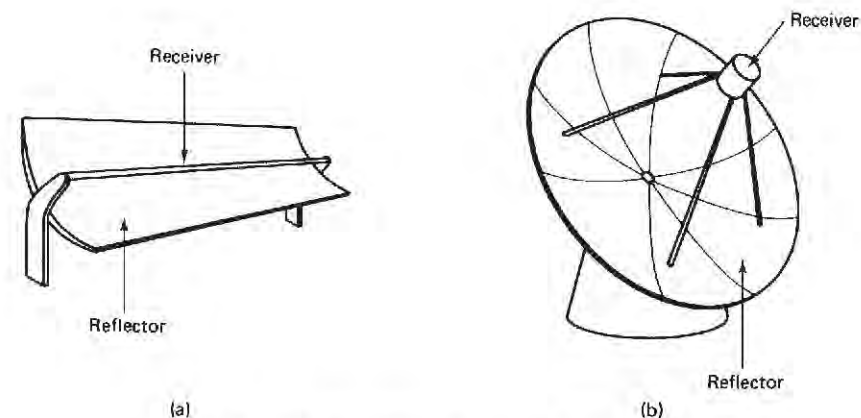


Figure 11.1. (a) Two-dimensional or linear concentrator. (b) Three-dimensional or point concentrator.

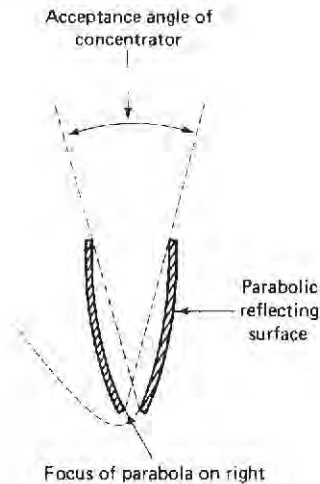


Figure 11.2. Schematic diagram of a nonimaging compound parabolic concentrator.

for a *three-dimensional* or *point-concentrating* system, as shown in Fig. 11.1(b). The range of angles of rays in direct sunlight due to the finite size of the sun's disk is about $\frac{1}{2}^\circ$ (9.4 mrad). This gives a maximum possible concentration of sunlight of 45,000 for a point-concentrating system.

The ideal performance of conventional concentrators such as focusing parabolas and lenses falls short of the limits of Eqs. (11.1) and (11.2) by a factor of 2 to 4 (Ref. 11.2). The first concentrator identified as having an ideal performance equal to these limits was the nonimaging compound parabolic concentrator (CPC) shown in Fig. 11.2. It consists of two parabolic reflectors aligned with their focal points lying in the positions shown.

11.3 STATIONARY AND PERIODICALLY ADJUSTED CONCENTRATORS

For stationary concentrators and those whose orientation is adjusted either daily or seasonally, it is clearly desirable to have as large an acceptance angle as possible consistent with obtaining high concentration. As an example, consider the case of a trough concentrator with its longitudinal axis lying in the east-west direction. The important variation in the direction of the sun's rays comes about due

to changes in the elevation of the sun. It can be shown that the solar elevation lies within $\pm 36^\circ$ of the plane of its path at the equinoxes for at least 7 h on any day of the year. Hence, an optimally designed stationary trough concentrator would concentrate sunlight for at least 7 h each day if its acceptance angle was 72° . The maximum concentration obtainable is $1/\sin(72^\circ/2)$, a very modest 1.7. Higher concentration ratios are possible if shorter minimum collection times are used or if the concentrator is designed to be periodically tilted.

Argonne National Laboratories fabricated small photovoltaic modules based on CPCs in 1976. One set of modules used parabolic reflectors; a second used total internal reflection within a solid acrylic block with the CPC shape (Ref. 11.3). These required seasonal adjustment to give concentration ratios of 7 to 9.

The preceding discussion indicates that the concentration obtainable for stationary concentrators is relatively low (considerably less than 3), whereas periodic adjustment increases achievable concentration ratios to about 12. The concentration obtained with a truly stationary concentrator may seem so marginal as to not warrant the extra complexity. However, one desirable feature, particularly for asymmetrical concentrators (Ref. 11.4), is that they can be used to boost the winter output of solar systems relative to the summer output. For stand-alone systems (Chapter 13), such a concentrator could not only decrease the cell area required but could also decrease the amount of energy storage required and the severity of cyclic drains on this storage.

One advantage of relatively low-concentration-ratio systems (<5 times) is that it may be possible to utilize cells fabricated in large volume for nonconcentrating applications and achieve the associated economies of scale. Higher-concentration-ratio systems require design changes in cells.

A novel approach to nontracking concentrators is the luminescent concentrator (Ref. 11.5). A sheet of glass or plastic is doped with a luminescent substance. A photocell is attached along one edge of the sheet and the other three edges are made reflective, as depicted in Fig. 11.3. Incident sunlight is absorbed by the dopant and then reemitted by luminescence in a narrow-wavelength range. A large fraction of the emitted light is trapped within the sheet either by total internal reflection or by reflection from the reflective edges until it reaches the attached photocell. The concentration obtainable with this system is not bounded by the limits mentioned previously. All angles of incidence can be accepted and maximum concentration is limited by practical considerations such as absorption of the emitted light in the sheet.

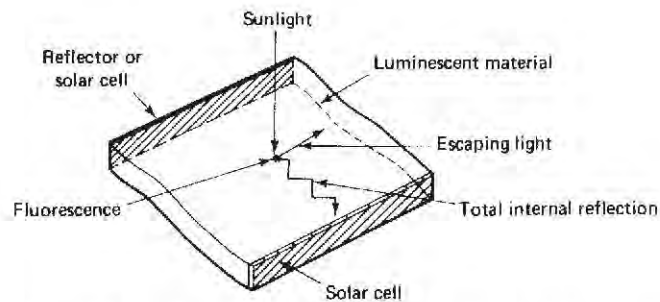


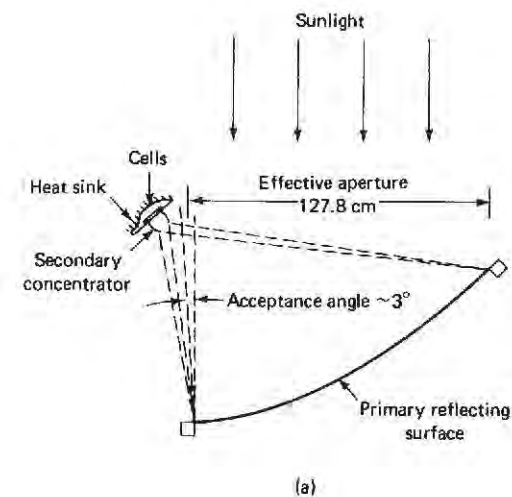
Figure 11.3. Luminescent concentrator. Absorbed sunlight is reemitted by luminescence with a large proportion trapped within the sheet by total internal reflection. The trapped light eventually reaches a solar cell.

11.4 TRACKING CONCENTRATORS

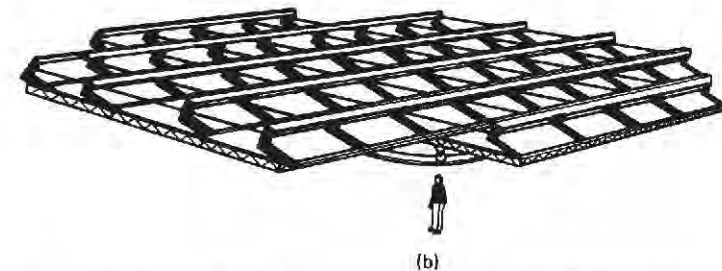
The mainstream of activity in the area of concentrating photovoltaic systems involves systems that concentrate sunlight by a factor greater than 20 and track the sun. Several diverse approaches to the design of such systems have been explored.

This diversity is brought out by two approaches to the design of a 10-kW subunit installed at Sandia Laboratories during 1978 and 1979. The first, shown in Fig. 11.4(a), uses a parabolic trough to concentrate sunlight onto a secondary concentrator and then onto the cell (Ref. 11.6). The overall geometrical concentration ratio is 25. This arrangement relaxes the precision required for the primary concentrator, although it does mean that two reflections are required, reducing the light reaching the cells to a maximum of 78% of that incident. Note the rather substantial heat sinking to keep the cells passively cooled. A 10-kW array mounted on a circular track for azimuth tracking is shown in Fig. 11.4(b).

An alternative approach shown in Fig. 11.5 uses refractive effects. A Fresnel lens has several advantages in this type of application. Note that the lens not only concentrates the sunlight but also provides an enclosure for the cell. The system shown uses a quad lens of this type to focus light onto cells mounted on a heat sink. With this design, the heat-sink area can be as large as the system aperture, keeping the cells reasonably cool even at the design concentration ratio of 40. A 2.2-kW array using this approach is shown (Ref. 11.7). A 350-kW_p system based on units similar to this was installed in Saudi Arabia during 1980 and 1981. At the time, this was the largest photovoltaic system deployed.



(a)



(b)

Figure 11.4. A 10-kW concentrating photovoltaic system based on a parabolic trough concentrator:

- (a) Concentrating elements and cell mounting.
 - (b) Overall system mounted on a circular track.
- (After Ref. 11.6, © 1978 IEEE.)

11.5 CONCENTRATOR CELL DESIGN

The ideal efficiency of cells *held at fixed temperature* increases with increasing concentration ratio. This is because the short-circuit current increases linearly with intensity, the open-circuit voltage increases logarithmically, and the fill factor increases with open-circuit voltage. The major difficulty in realizing this efficiency advantage is the increased importance of series resistance losses at high current densities. Since the cell efficiency determines the area of concentrating elements required for a given power output, it is critically important to achieve as high an efficiency as possible.

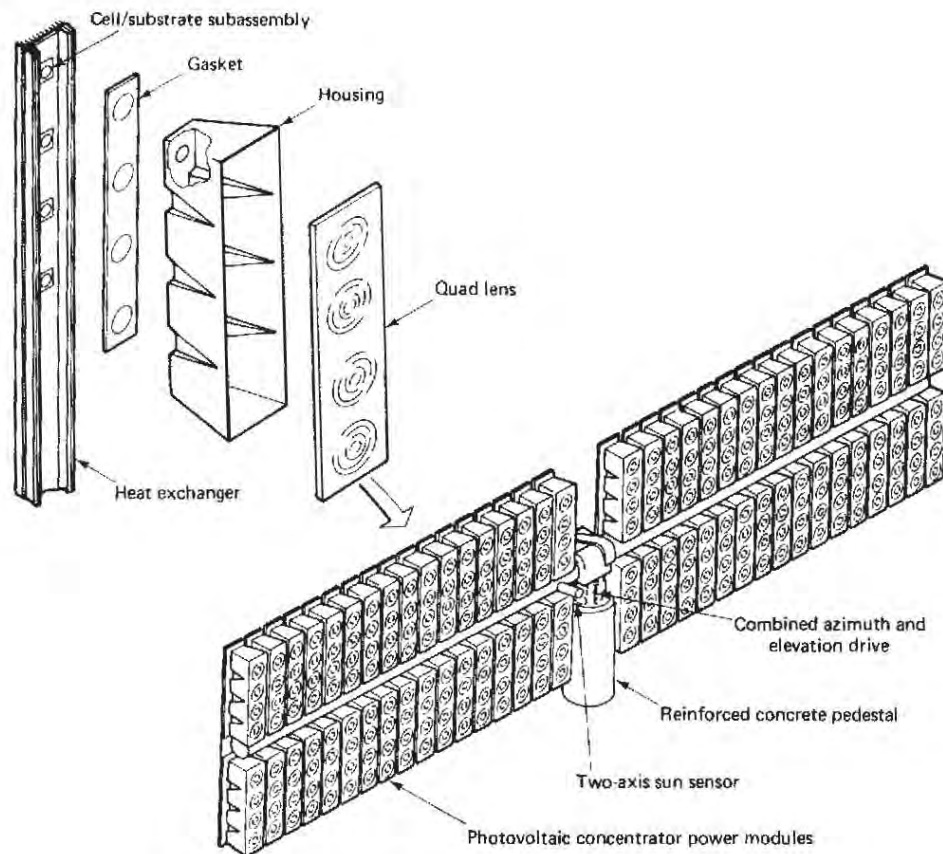


Figure 11.5. A 2.2-kW concentrating system based on Fresnel lenses. The lenses not only concentrate the sunlight but form part of the cell housing. In this design, the area of the heat sink is comparable to the system aperture. (After Ref. 11.7, © 1978 IEEE.)

The following suggestions could be made to minimize the resistance of a solar cell: (1) use of a low-resistivity substrate with a back surface field region for low bulk and contact resistive losses, (2) minimization of the sheet resistivity of the normally diffused thin top layer, (3) use of a top contact design with a fine finger pattern to minimize resistive losses due to lateral current flows, and (4) use of thick metal contact layers to reduce resistive losses in fingers and busbars.

All these steps are normally taken to produce present concentrator cells. Lower-resistivity substrates have been used than are

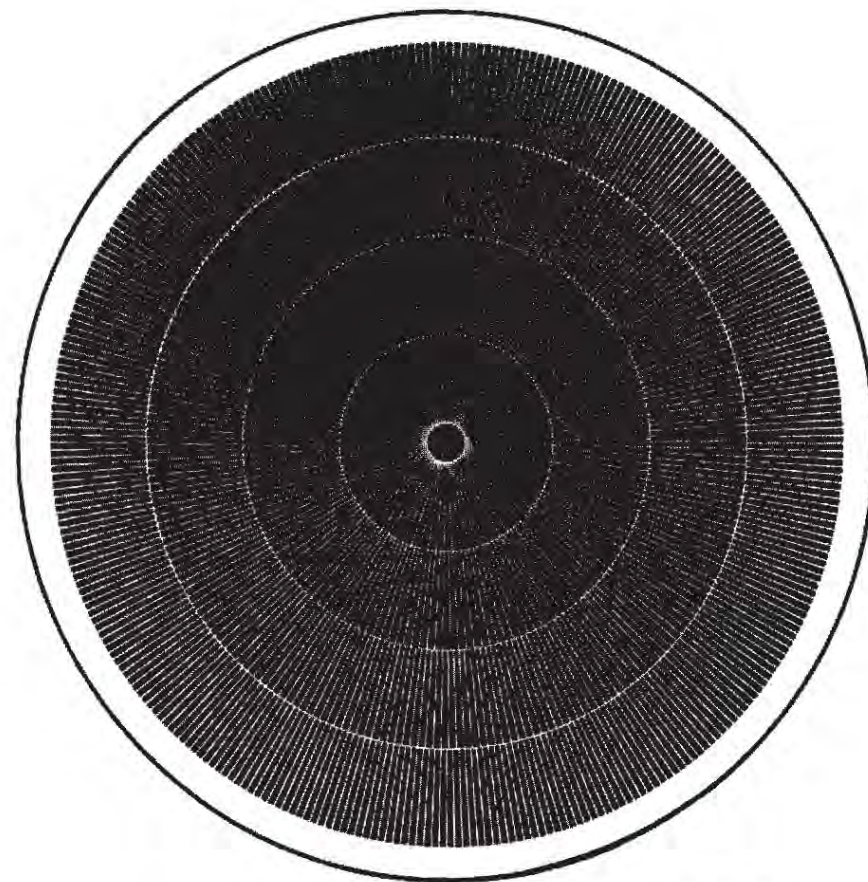


Figure 11.6. Typical concentrating cell for a point-focusing system. (Cell courtesy of Applied Solar Energy Corporation.)

used in normal cells.¹ The sheet resistivity of the diffused layer is kept reasonably low. However, striving for too low a value can give rise to the performance degradation effects described in Chapter 7. Each technology for defining the top contact places a lower limit to how fine it can be made. This limit also depends on the thickness of the metal required in the top layer. As a rule of thumb for the

¹Because of 'high injection' effects, the series resistance of cells on high resistivity substrates with a back surface field can be kept low under some conditions. This provides an alternative approach to making concentrator cells. See the footnote in Section 8.4 and the reference therein.

dimensions involved, such lines can be made only about half as thick as they are wide. The normal practice has been to deposit the top contact metals by vacuum evaporation, define the pattern required using photolithographic methods, and then build up the lines as thick as possible by electroplating silver.

For concentrating, cells are normally designed to have their top surface only partially illuminated. For example, for the typical contact design of Fig. 11.6 for point-concentrating systems, the area not covered by the busbar around the edge is the design area. Efficiencies are based on the amount of light reaching this design area *rather than on the total cell area*. The form of the efficiency variation as a function of concentration ratio at fixed cell temperature is shown in Fig. 11.7. The general trend is an increase in cell efficiency with increasing concentration ratio for low values of this ratio and a decrease in cell efficiency at high values. The peak efficiency may occur at concentration ratios anywhere between 20 and several hundred suns. The increase at low concentrations is due to the logarithmic increase of voltage output with increasing current density. At high current density, series resistance losses become important and decrease the efficiency by decreasing the fill factor.

Peak efficiencies in excess of 20% have been reported for silicon concentrating cells (Ref. 11.8) compared to about 25% for cells based on GaAs (Ref. 11.9). Actual operating efficiencies tend to be somewhat lower than this because cells in concentrating systems are likely to operate at relatively high temperatures due to increased power densities. Optical losses reduce system efficiencies further. Designers of concentrating systems would be very pleased

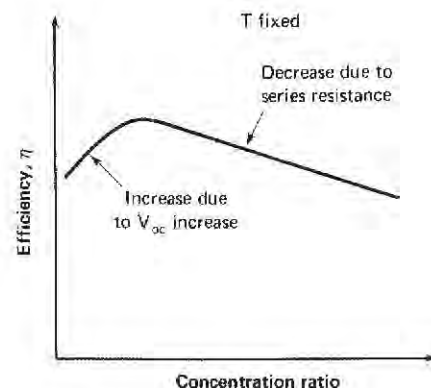


Figure 11.7. Schematic diagram showing the typical variation in efficiency of a solar cell held at fixed temperature as the concentration ratio is increased.

if they were able to design systems where 85% of the light striking the system aperture reached the cells.

11.6 ULTRA-HIGH-EFFICIENCY SYSTEMS

11.6.1 General

The energy-conversion efficiency of the photovoltaic section of a concentrating system is a key parameter in determining the cost of the system. It determines the system aperture for a given output. In the following sections, concepts that result in exceptionally high energy-conversion efficiencies will be explored. This ability to obtain very high efficiencies is one aspect of concentrating systems that makes them a distinctly different alternative to flat-plate modules.

11.6.2 Multigap-Cell Concepts

Selecting the optimum band gap for the solar cell material can be regarded as a trade-off between choosing the band gap narrow enough so that not too many photons are lost because they have insufficient energy to create electron-hole pairs, yet wide enough so that not too many waste their energy by creating electron-hole pairs with energy well in excess of the band gap.

A more efficient system can be produced if the low-energy photons in sunlight are directed to solar cells made from narrow-band-gap semiconductors in which they can be utilized. The high-energy photons are directed to wide-band-gap cells, where their energy is not dissipated by creating electron-hole pairs with energies grossly in excess of the band gap.

Two concepts for directing light to cells of appropriate band gap are shown in Fig. 11.8. The first, known as *spectrum splitting*, uses spectrally sensitive mirrors to direct the light to appropriate cells. The second, the *tandem cell* approach, uses a series of cells stacked on top of each other with the widest-band-gap material uppermost. Low-energy photons will pass through the stack until they reach a cell of low enough band gap to utilize them. Since both schemes involve extra complexity compared to a single cell, the multicell concept is best suited to systems using high concentration ratios.

The maximum efficiency obtainable with this approach depends on the number of different band gap cells used. Table 11.1

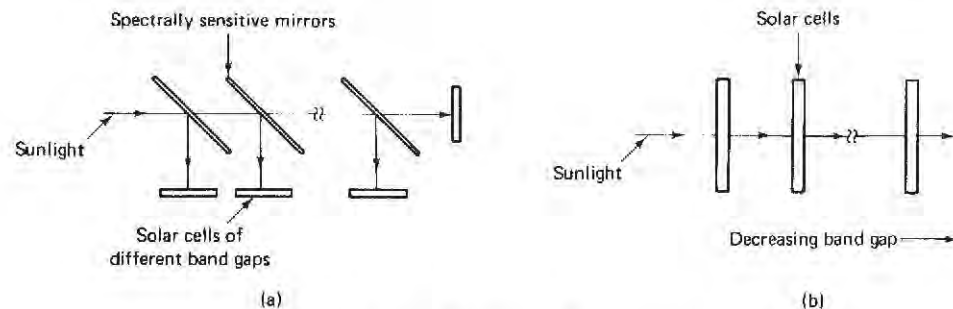


Figure 11.8. Multigap-cell concepts:

- (a) Spectrum-splitting approach.
(b) Tandem-cell approach.

shows this variation as well as the optimum band gaps for the cells. The efficiencies quoted are for sunlight concentration of 1000 suns (AM1). The ideal values are plotted in Fig. 11.9(a). It can be seen that this approach ideally doubles the limit efficiency compared to a single-cell system. In actuality, such a system will create additional unavoidable optical losses compared to a single-cell system. Including optimistic values for these losses reduces the efficiencies to the more conservative values shown in Fig. 11.9(b). The advantage of multiple cells is reduced to 20 to 50%.

Considering a two-cell system, silicon is not an optimum choice for the low-band-gap cell. However, a silicon cell (band gap

Table 11.1. OPTIMUM BAND GAPS AND EFFICIENCIES FOR MULTIGAP CELLS (1000 X AM1)

Number of cells	System efficiency (%)		Band gaps (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	56.3	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			
9	61.3	0.6	0.8	1.0	1.4	1.6	1.8	2.0	2.2	2.6		
10	61.6	0.6	0.8	1.0	1.4	1.6	1.8	2.0	2.2	2.4	2.6	
11	61.8	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6

Source: After Ref. 11.10.

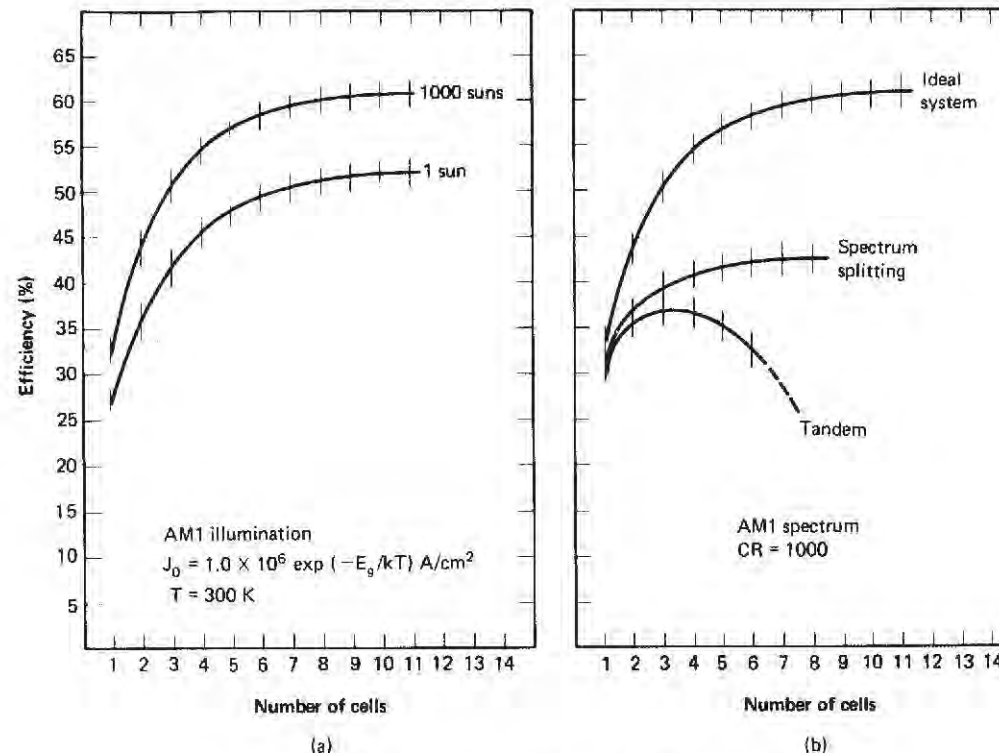


Figure 11.9. (a) Maximum efficiency for multigap cells for concentrated and unconcentrated sunlight. (b) Effect of optical losses.
(After Ref. 11.10, © 1978 IEEE.)

of 1.1 eV) combined with a material with a band gap in the region 1.6 to 2.1 eV gives close to the optimum performance (Ref. 11.11). The first really striking experimental results for the multigap approach were obtained in 1978 for a system consisting of a silicon cell and a $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterojunction cell (Ref. 11.11). The band gap on the lower-band-gap side of the heterojunction was 1.61 eV. A wavelength-selective mirror was used to reflect photons of energy less than 1.65 eV onto the silicon cell, with the remainder passing through to the heterojunction cell. Under 165 suns concentration, the combined output of the system corresponded to an efficiency of 28.5%, the highest efficiency obtained for any photovoltaic system at the time.

With the multigap approach, the voltage output of each band-gap cell and generally the current output will be different. It is of course possible to have an individual circuit for each cell type at the

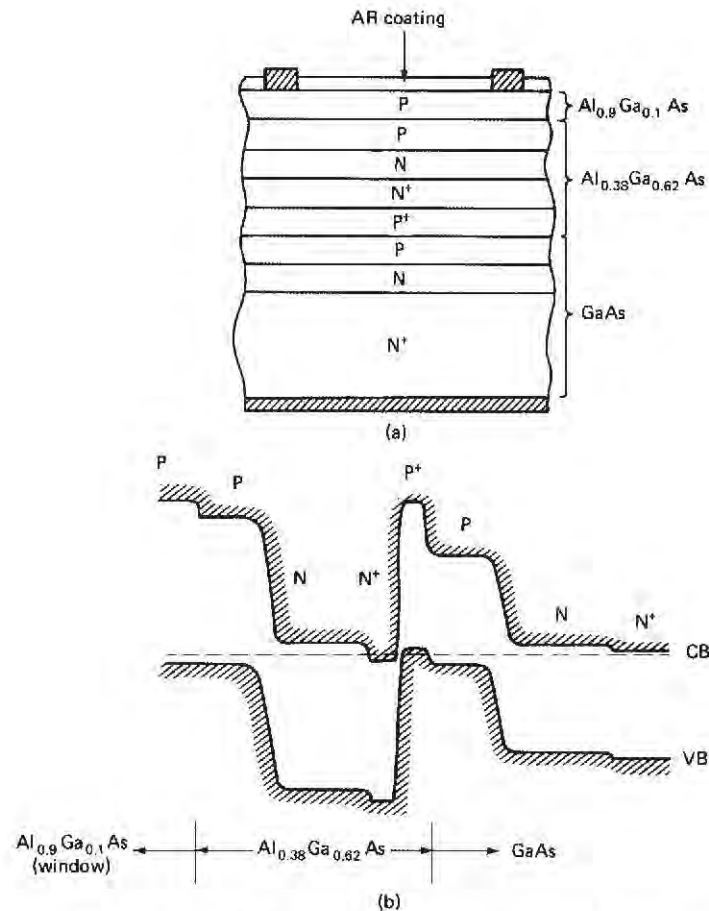


Figure 11.10. (a) Two series-connected tandem cells formed by epitaxial processes on the one substrate. (b) Corresponding energy-band diagram.

expense of increased complexity. A second alternative is to connect the cells in series. As mentioned in Section 6.6.4, the current output of series-connected cells is that of the worst cell. To maintain the efficiency of the multicell configuration, it is necessary to design the different types of cells so that each has the same short-circuit current. It has been suggested that this is also a reasonable criterion for selecting cell band-gaps to obtain maximum efficiency (Ref. 11.11).

An interesting idea in this area is the construction of tandem cells series interconnected on the one substrate. This can be accomplished using the same type of epitaxial growth technique as used to produce GaAs-based cells, as described in Section 10.4. For

example, Fig. 11.10 shows the device structure and energy-band diagram of a solar cell structure that corresponds to two series-connected tandem cells (Ref. 11.12).

The top layer acts as a window layer for the underlying $\text{Al}_{0.38}\text{Ga}_{0.62}\text{As}$ cell. Under this cell are two heavily doped layers having several functions. These act as a back surface field for the top cell and a front surface field for the lower cell. The width of the depletion region at their junction is very thin and electrons can flow between the conduction and valence band at this junction by quantum mechanical tunneling process. This region consequently acts as the series connection between the cells, as well as an optical window for the underlying GaAs. Structures of this complexity are well within the bounds of the technology developed for fabricating semiconductor injection lasers (Ref. 11.13).

An important question for series-connected multigap cells is whether there are large variations in the relative spectral content of sunlight during the normal operating conditions of the cells. Such variations will cause changes in the relative values of the current output of the cell and have a pronounced effect on system efficiency. Preliminary data on this point indicates that, although variations can occur because of clouds and near sunset, this is not expected to be a major loss mechanism (Ref. 11.11).

11.6.3 Thermophotovoltaic Conversion

One important loss in solar cells is due to the fact that photons with energy far in excess of the band gap create only one electron-hole pair. Their effect on the cell output is consequently the same as a photon of much lower energy. Figure 11.11(a) shows

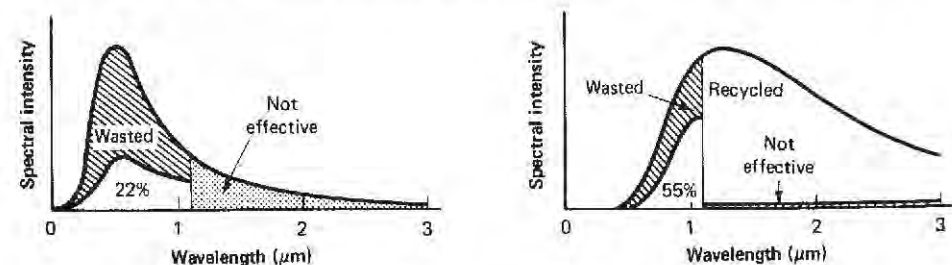


Figure 11.11. Utilization of the energy incident upon a silicon solar cell when illuminated by black body radiation at two different temperatures:

(a) 6000°C. (b) 2000°C.

(After Ref. 11.15.)

the fate of the incident energy as a function of wavelength for a silicon cell.

If a solar cell is illuminated by a black body at lower temperature (2000°C), the situation is modified as shown in Fig. 11.11(b). More of the energy would be utilized in those photons that are more energetic than the band gap. The efficiency of the solar cell would actually decrease, because relatively fewer photons would have energy larger than the band gap. However, if most of these ineffective photons could be redirected to the black body, thus contributing to maintaining its temperature by being absorbed in it, the situation changes. Such photons are no longer useless, but supply part of the energy required to hold the black body at high temperature.

In thermophotovoltaic solar energy conversion (Ref. 11.14), the sun is used to heat a radiator to high temperatures; the radiator then reemits radiation onto a solar cell. The long-wavelength radiation the cell cannot use is recycled to the radiator. The essential parts of a thermovoltaic converter are shown in Fig. 11.12. The rear of the cell is made highly reflective so that long-wavelength radiation passing through it is reflected back to the radiator. Although the theoretical upper limit of efficiency is very high for this concept, the fact that it involves several processes in series ensures that experimental efficiencies will be more modest (Ref. 11.15).

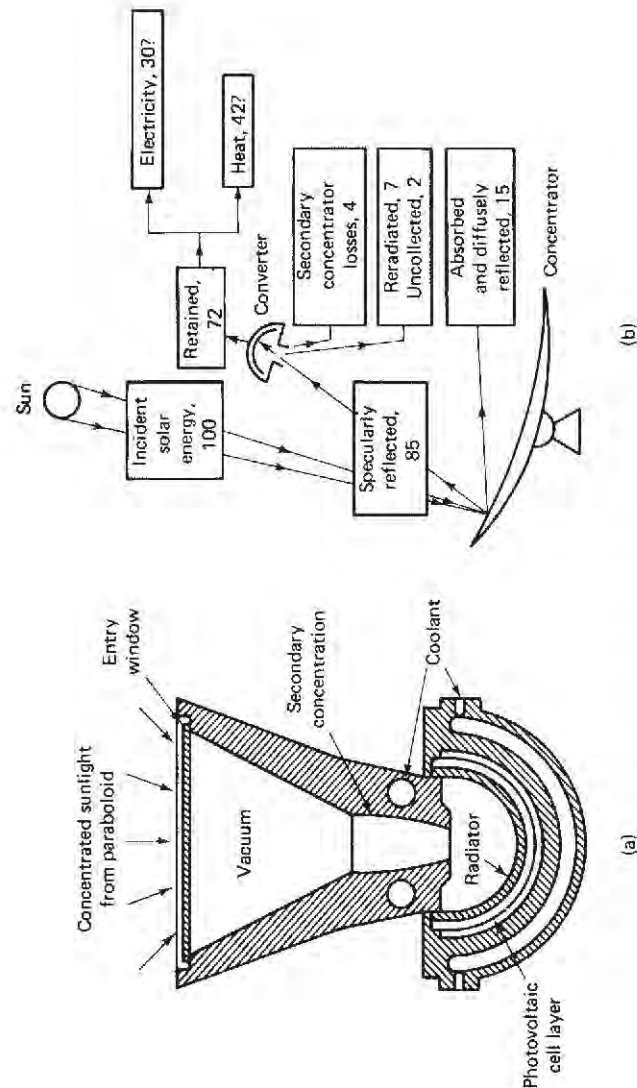


Figure 11.12. (a) Essential parts of a thermophotovoltaic solar energy converter. (b) Corresponding energy-conversion system and possible energy budget. (After Ref. 11.15.)

11.7 SUMMARY

Concentration of sunlight displaces the cost of a photovoltaic system from the cells to the cost of the concentrating and tracking elements. Continuous tracking of the sun is required to maintain concentration ratios greater than about 12.

Upper limits to cell efficiency at fixed temperature increase with increasing concentration ratio. This beneficial effect is offset by the generally higher cell operating temperatures when used in concentrating systems. For low concentration ratios, passive cooling of the cells is workable. For concentration ratios greater than about 50, active cooling such as by circulating water is required. This gives rise to total energy systems that produce both electricity and thermal energy from sunlight.

In concentrating systems, cell efficiency can be a more critical parameter than cell cost. This allows relatively complex schemes for increasing photovoltaic efficiency to be implemented. Concepts based on using several different band-gap cells to convert different parts of the sun's spectrum are likely to result in system efficiencies

above 30%. Modifying the spectral content of sunlight as in the thermophotovoltaic effect could also result in similar efficiencies.

EXERCISES

- 11.1. Consider the case of a luminescent concentrator of Fig. 11.3. If the light reemitted by luminescence is emitted with uniform intensity in all directions, calculate the percentage trapped within the sheet by total internal reflection for the case where the point of emission is midway through the sheet. Assume that the sheet refractive index is 1.5.
- 11.2. A silicon shallow junction solar cell has a top-layer sheet resistivity of $30 \Omega/\square$. At 1 sun, it gives its maximum power output at 450 mV and a current density of 30 mA/cm^2 . Estimate the maximum spacing permissible between the fingers of the top contact to the cell to give a power loss due to lateral current flow in the top layer of less than 4% at 100 suns' operation.
- 11.3. At 1 sun operation (100 mW/cm^2), a solar cell gives an open-circuit voltage of 0.60 V and a short-circuit current of 0.6 A at 300 K. The design area of the cell is 20 cm^2 , its ideality factor is 1.2, and its series resistance is 0.007Ω . Assuming that the latter two parameters do not vary with light intensity, calculate and sketch the expected efficiency of this cell at 300 K as a function of concentration ratio over the range 1 to 50. [Use Eq. (5.17) to calculate the effect of series resistance on solar cell output.]
- 11.4. By referring to Fig. 5.1(b), select the ideal band gap under AM1.5 illumination for the second cell in a two-cell series connected tandem arrangement if the other cell is (a) silicon ($E_g = 1.1 \text{ eV}$); (b) gallium arsenide ($E_g = 1.4 \text{ eV}$). Calculate the limiting efficiency in each case under AM1.5 (83.2 mW/cm^2) and $1000 \times \text{AM1.5}$ irradiation if the cell temperatures are held at 300 K.

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Chapter 12

PHOTOVOLTAIC SYSTEMS: COMPONENTS AND APPLICATIONS

12.1 INTRODUCTION

In previous chapters, the properties of the most important part of any photovoltaic system, the solar cells themselves, have been treated in some detail. In this and the following chapters, the other components required for a photovoltaic system will be described, as will the performance and commercial viability of overall systems.

Since the output of solar systems is intermittent and unpredictable in the terrestrial environment, some form of energy storage and/or auxiliary energy supply is required if the system is to supply power on demand. The range of available and potential storage options will be explored.

Solar cells generate a dc (direct-current) output. The voltage at which the maximum power can be extracted changes with sunlight intensity and cell temperature. Since electrical power is most commonly utilized in ac (alternating-current) form, some form of power conditioning is required between the solar cell modules and the elec-

trical load. The general features desirable for power conditioning equipment are also outlined.

In the past the costs of solar cells have restricted their commercial use to relatively small stand-alone power supplies in remote regions. With the continuing reduction in cell prices, the range of commercially viable applications expands (Ref. 12.1). Some of these are described in the following sections.

12.2 ENERGY STORAGE

12.2.1 Electrochemical Batteries

Electrochemical batteries have been the predominant choice for storage for photovoltaic systems installed in the past. Lead-acid batteries and, to a lesser extent, nickel-cadmium batteries have been used. The major difficulty with this form of storage is its high cost together with the vast amount of material required to implement it on a large scale.

Several alternative battery systems are under development for potential use in electric vehicles and for short-term storage ("load leveling") in electricity supply systems (Ref. 12.2). These hold the promise of substantially lower battery costs for photovoltaic applications in the future (Ref. 12.3). The most promising systems at the present point include the zinc-chlorine and high-temperature batteries such as the sodium-sulfur and lithium-iron sulfide.

One development in the area of electrochemical storage that seems particularly well suited to stand-alone photovoltaic systems is the redox battery (Ref. 12.4). The concept of a *redox couple* was introduced in Section 9.7.2. The term refers to oxidized and reduced states of a species within solution. In a redox battery, two separate redox couple solutions are kept largely isolated from each other. During charging, one couple is oxidized while the couple in the other solution is reduced. The opposite occurs during discharge.

The redox-couple solutions that have received the most attention are acidified chloride solutions of chromium (redox couple: $\text{Cr}^{2+}/\text{Cr}^{3+}$) and iron (redox couple: $\text{Fe}^{2+}/\text{Fe}^{3+}$). Figure 12.1 shows how these are arranged to form a redox system in its simplest form. Each tank contains one of the redox-couple solutions. These solutions are pumped through the power-conversion section, where they are kept separated by a highly selective ion-exchange membrane. Electrical contact is made to each solution by an inert carbon elec-

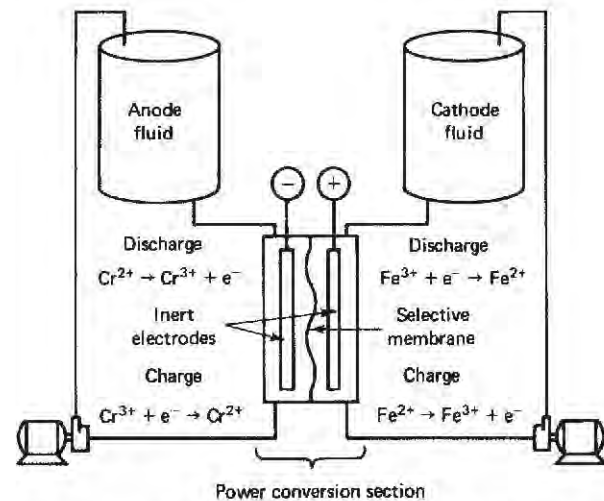


Figure 12.1. Schematic diagram of an electrically rechargeable redox energy storage system. (After Ref. 12.4.)

trode. The membrane prohibits the passage of iron and chromium ions but allows easy passage of chloride and hydrogen ions.

When the storage system is charged, the chromium solution contains chromium ions mostly in the reduced (Cr^{2+}) state, while the iron solution has its ions in the oxidized (Fe^{3+}) state. In the discharge mode, the following reactions occur:

1. At the anode the chromium ions are oxidized:



2. At the cathode, the iron ions are reduced:



3. Across the membrane, H^{+} ions move from anode to cathode and Cl^{-} ions move in the opposite direction to maintain neutrality.

Electrons flow in the external circuit from the anode to the cathode, allowing current to be extracted from the cell terminals. A voltage impressed across the cell terminals encourages the reaction to proceed in the opposite direction, charging the cell. A number of these cells can be connected in parallel hydraulically and in series electrically to increase the voltage output.

A feature of the redox system that differs from common batteries is the independent sizing of the system power by the size of the power-conversion section and of the storage capacity by the selection of tank volumes and solution concentrations. This feature makes the system ideal for stand-alone photovoltaic systems, where storage of 1 week or more may be required to cover periods of low sunshine. The relatively mild solutions permit the use of inexpensive plastic materials for storage tanks and pipes. There is also no fundamental limitation to the number of charge/discharge cycles the system can tolerate, and operating lives up to 30 years have been predicted. The disadvantage of the approach lies in the relatively low power density of the electrolytes. A given volume of charged solutions can produce the same amount of electricity as about $\frac{1}{100}$ the volume of petroleum-based fuels, although a major difference is that the solutions can be recharged.

12.2.2 Large-Capacity Approaches

Batteries are an energy storage medium suited for both very small and very large photovoltaic systems. As discussed in Chapter 14, energy storage as an element of conventional electricity supply networks acts to improve the viability of including solar electric generation into the system. In this regard, it is worth noting that several large-capacity energy storage techniques are already being incorporated into such networks.

The most established technique for storing electrical energy on a large scale is *pumped hydro storage*. During periods of low demand, energy is stored by pumping water from a reservoir at a low level to a reservoir at a higher level. During periods of high demand, water is allowed to flow in the opposite direction to drive turbines, generating power. About two-thirds of the original electrical energy can be recovered in this approach. This method is presently limited by the shortage of suitable sites. A proposed development of this system in which the lower reservoir is constructed several hundred meters underground in hard rock eliminates this disadvantage to some extent. The larger "heads" obtainable also reduce the size of the upper reservoir for a given storage capacity (Ref. 12.2).

In a *compressed-air* energy storage plant, excess energy is used to store compressed air in an underground reservoir. Although this technique is more complex in practice than the pumped hydro method, it does have the advantages of a higher density of energy storage and greater flexibility in siting the underground reservoir

(Ref. 12.2). Installations can be smaller and still be economically viable. The world's first commercial installation at Huntorf in West Germany has an operating capacity of over $\frac{1}{2}$ million kilowatt-hours. Pumped hydro storage has to be an order of magnitude larger to obtain the full economic benefit.

Storage of electrical energy by conversion to hydrogen is another possible route well suited to photovoltaics because of the low-voltage dc requirements of electrolysis. In fact, as seen in Section 9.7.3, photoelectrolysis can be achieved directly at the surface of a semiconductor, although present efficiencies are low. Hydrogen has several advantages as an energy storage medium. It can be economically transferred over large distances by pipeline. It is suitable for use as a fuel in conventional engines for motive power or in a fuel cell to generate electricity efficiently. These features lead to concepts of a *hydrogen economy*, where hydrogen forms the basic fuel for mankind (Ref. 12.5). From the point of view of storage for photovoltaics, a major disadvantage involves the present low storage efficiencies (<50%) attainable.

Storage in superconducting magnets or as mechanical energy in flywheels are other possibilities, although both seem intrinsically more expensive than other alternatives at the present time.

12.3 POWER CONDITIONING EQUIPMENT

A photovoltaic system in general may consist of the cells, a storage medium, some form of backup either in the form of an auxiliary generator or the electricity supply grid, and electrical loads, either ac or dc. Power conditioning and control are required to provide an interface between these different system elements. This is illustrated schematically in Fig. 12.2.

The simplest solar cell system is one in which the cells can be connected directly to the load, supplying power whenever there is adequate illumination. Water pumping using a dc motor to drive the pump is an example of such a system. The next simplest systems are those in which a dc load is to be supplied in a situation where sufficient battery storage can be installed so that no backup generator is required. In this case, all that may be required is a *regulator* to prevent damage to the batteries by overcharging in sunny periods. At the next level of complexity, a similar system is used to provide power to an ac load. In this case, an *inverter* is required to convert the dc output of the solar cells and storage batteries to alternating form. At a higher level of complexity, a backup generator (which

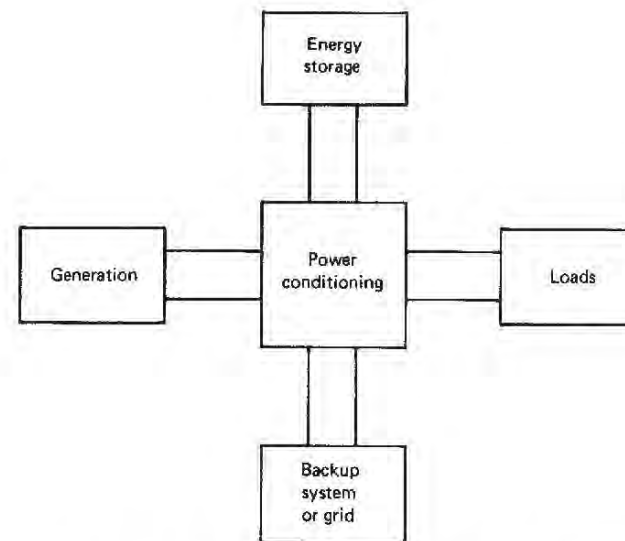


Figure 12.2. Power conditioning equipment in the most general case serves not only as an interface between the different components of a photovoltaic system but also performs control and protection functions.

may be the electricity supply grid) is also involved. In this case, some form of control is required to determine when the auxiliary supply is operated.

The major developmental effort in the area of power conditioning is in improving the performance and lowering the cost of inverters. Key performance parameters are efficiency and no load power drain (Ref. 12.6).

12.4 PHOTOVOLTAIC APPLICATIONS

In the past, the high costs of solar cells restricted their commercial use to applications where small amounts of power were required in regions remote from an electricity supply grid. Telecommunication systems formed the backbone of this commercial market. These have ranged from microwave repeater stations requiring several peak kilowatts of generating capacity per station to small modules rated at only tens of watts for remote-area radio telephone services.

Other reasonably large uses have been in powering navigational aids and warning devices, railway crossings, weather and pollu-

tion monitoring equipment, corrosion protection using the impressed current technique, as well as in powering consumer products such as calculators and watches. Cells have also been used for powering educational television in developing countries and for providing refrigeration in conjunction with immunization programs in such countries.

As cell costs continue to decrease, other applications particularly relevant to developing countries have become economically viable (Ref. 12.7). Examples are water pumping for irrigation on a small scale and water purification to provide drinking water. Developmental aid programs may be one way of supplying cells to this market which would overcome likely problems with raising capital for such systems.

The first application of photovoltaics likely to have a measurable impact on world energy demands is in supplying residential power in North America. In the mode of operation envisaged, the residence would also be connected to the grid which would act as a long-term storage medium, as discussed in Chapter 14. Several of the technologies based on silicon discussed in Chapter 7 appear capable of producing cells at a cost consistent with this use.

For larger-scale generation of power, such as in a central power plant of large capacity, cells have to be about half the cost as in this residential use to be competitive. A technology based on thin-film solar cells has a much higher probability of reaching these costs. Other desirable features for this mode of operation are discussed in Chapter 14.

12.5 SUMMARY

In any photovoltaic system, components other than the solar cells alone are required in all but a few applications. A photovoltaic system may involve the cells, energy storage, power conditioning and control equipment and a backup generator. The major item of power conditioning equipment is generally an inverter to convert the dc output of cells and battery storage to the alternating form often required by the load.

In the past, the commercial use of solar cells has been restricted to supplying relatively small amounts of power in remote areas. In the future, a much wider range of applications will become viable as cell costs continue to decrease. The supply of residential power in grid-connected areas of the United States is seen as a potentially large application that is economically workable with technology presently at an advanced stage of development. To be usable for

the generation of power in a large-capacity central power plant, cell costs need to be about half that required for the residential application. A thin-film technology that uses minimal semiconductor material is the approach most likely to produce cells at such costs.

EXERCISE

- 12.1. Battery storage is required for a photovoltaic system that has to supply a peak load of 10 kW and an average load of 1 kW. Assume that an advanced lead-acid battery capable of supplying peak load costs \$100 per kWh of storage, whereas a redox battery costs \$300 per kW peak rating of the power conversion section plus \$40 per kWh of energy storage. Which system would cost less to purchase for: (a) 4 h of storage; (b) 5 days of storage?

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Chapter 13

DESIGN OF STAND-ALONE SYSTEMS

13.1 INTRODUCTION

The major commercial market for photovoltaic systems in the past has been for small, reliable power supplies in remote areas. These generally operate without any nonsolar backup and are therefore the sole source of electric power for the load. The design of such systems is discussed in this chapter.

A schematic of a simple solar-powered system is shown in Fig. 13.1. The load for most such small systems utilizes power in the dc form as generated by the solar cells. In addition to the array of solar cell modules and storage batteries, the other system components are a blocking diode to prevent loss of battery charge through the cells overnight and a regulator to prevent overcharge of the battery in periods of high insolation levels.

13.2 SOLAR MODULE PERFORMANCE

Present solar cell modules generally contain sufficient series-connected solar cells to generate enough voltage to charge a 12-V

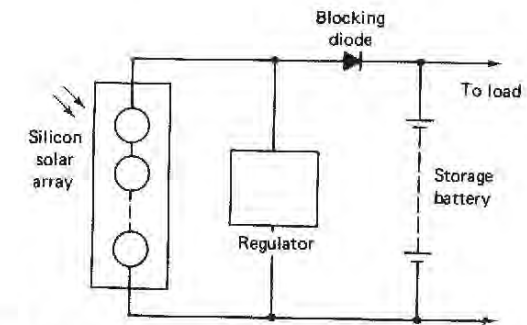


Figure 13.1. Simplified stand-alone solar power system. (After Ref. 13.2.)

battery. Modules are connected in series to increase the system voltage output and in parallel to increase the output current of the system. The number of series-connected cells required to charge a nominally 12-V system is higher than first expected for a number of reasons. For lead-acid batteries, over 14 V is required to fully charge a nominally 12-V battery. If a silicon blocking diode is used, a further 0.6 V at the minimum is required to forward-bias it. Additionally, module temperature frequently will exceed 60°C in the field. The open-circuit voltage of the module decreases by about 0.4% for each 1°C increase in temperature (Section 5.3). This means that there will be about a 3-V reduction in open-circuit voltage for a module with a 20-V open-circuit voltage specified at 25°C. As indicated in Section 6.6.2, different module designs will cause cells to reach different temperatures in the field. Modules mounted to allow air circulation at the rear will run cooler than those without this feature.

For best performance, modules are mounted so that they face south in the northern hemisphere and north in the southern hemisphere at an angle from the horizontal which depends on the latitude of the site. For maximum output over the year, this angle approximately equals the latitude angle. For systems as described in this chapter with 10 to 30 days of battery storage, the optimum value of this angle increases by about 15° to boost the winter output of the system.

A module designed to charge a 12-V battery will generally be able to generate sufficient voltage during daylight hours to do so. The current output will be very closely proportional to the intensity of sunlight on the module. Hence, the focus of attention in the

design of the systems of the present chapter is on the current output of the module.

A final consideration regarding module performance is the effect of accumulated dust. This will be a cyclic effect with minimum blocking occurring after rain. For glass-covered modules, available data indicate that the loss due to this effect averages 5 to 10%.

13.3 BATTERY PERFORMANCE

13.3.1 Performance Requirements

The feature of photovoltaic systems that makes them competitive at present prices is high reliability and low maintenance costs. To achieve these characteristics, systems are designed with large secondary battery stores to tide them over the worst conceivable insolation periods. Battery maintenance is, in principle, the major maintenance requirement of stand-alone photovoltaic systems.

With such large battery storage, the charge/recharge cycle imposed on the battery is a seasonal cycle in which the battery charges during the summer and discharges during winter. Superimposed upon this seasonal cycle is a much smaller daily cycle in which the battery charges during the day and loses a small percentage of its charge at night. Because of the seasonal nature of the storage, a battery with low self-discharge characteristics is essential. High charge storage efficiency (ratio of charge that can be extracted from battery to charge put into battery) is also desirable.

13.3.2 Lead-Acid Batteries

The most commonly used batteries for solar systems have been lead-acid batteries. Lead-antimonial types as commonly used in automobiles are not suitable for professional solar systems because of their high rate of self-discharge (up to 30% of capacity per month) and low life.

Commercial batteries most suited for stand-alone power supplies have been those intended for *stationary* or *float* service. These are designed for applications such as serving as emergency power sources in uninterruptible power supplies. In this use, the batteries are kept fully charged but immediately take up the load demand if the primary power source fails. Operating life in this type of application is generally in excess of 15 years. These batteries are normally rated at an 8- or 10-h discharge rate and have either lead-calcium or

pure lead plates. More recently, this type of battery has been developed to meet the specific requirements of the photovoltaic mode of operation (Ref. 13.1).

In the type of solar system described in this chapter, the battery will operate in a fairly unusual mode whereby it remains fully charged in summer but only partially charged through most of the winter. Long periods in a low state of charge can cause much larger crystals of lead sulfate to form on the battery plates than the small crystals which normally form during discharge. This process, known as *sulfation*, leads to loss of capacity and reduced battery life. Good design practice is to ensure that the battery store is large enough so that it retains a reasonable percentage of full charge during the winter months. This will also ensure that the concentration of sulfuric acid in the electrolyte solution remains relatively high in these months, reducing the possibility of freezing (Ref. 13.1).

During summer, solar cells will be generating excess power over that required by the load and it would be possible to overcharge the battery. This is undesirable on several accounts. It can cause the evolution of hydrogen and oxygen from the battery, a process known as *gassing*, with associated loss of electrolyte and safety hazard. It can also lead to excessive plate growth and the shedding of active material from the plates, reducing battery life. On the other hand, good practice with lead-acid batteries is to allow for a periodic boost charge. The resultant gassing agitates the electrolyte, preventing *stratification* of more concentrated material in lower regions. An overcharge or *equalizing charge* also ensures that weaker cells in the battery have the opportunity to become fully charged (Ref. 13.1).

Figure 13.2 shows how the voltage across a battery cell varies with the amount of charge stored in it when charged with a constant

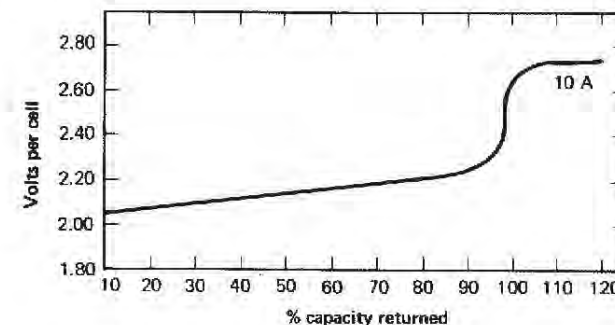


Figure 13.2. Constant-current charging characteristics of a lead-acid battery suitable for solar use. (After Ref. 13.2.)

current. At about 95% recharged, there is a sharp rise in voltage across the cell. This corresponds to the gassing point. To restrict the amount of gassing, at the same time providing for the beneficial effects of a periodic overcharge, a reasonable compromise is to use a voltage regulator to restrict the voltage per battery cell to about 2.35 V for the case shown (Ref. 13.2).

Other relevant considerations are the variation in battery capacity with rate of discharge and temperature. Battery capacity is usually specified at a given discharge rate. For example, Fig. 13.3 shows the measured ampere hours extracted from a battery at two different discharge rates. The battery capacity was specified as 550 A-h when discharged to 1.85 V per cell at a 10-h rate (55 A drawn continuously for 10 h). The battery capacity at the 10-h rate can be seen to be above specifications. At the 300-h rate that is more typical of solar operation, the battery capacity is nearly double the specified value. It follows that in designing a solar system, not only the battery capacity but also the discharge rate at which it is specified are important.

The storage capacity decreases with temperature, which is unfortunate because winter is when most use is made of storage. As a rule of thumb, capacity decreases by about 1% per °C below about 20°C. This, together with the possibility of freezing the electrolyte, makes it desirable to insulate the battery from abnormally cold environments. At the other extreme, high temperatures accelerate battery aging mechanisms, increase the rate of self-discharge, and increase the use of electrolyte. Again, the batteries require suitable housing to avoid high temperatures.

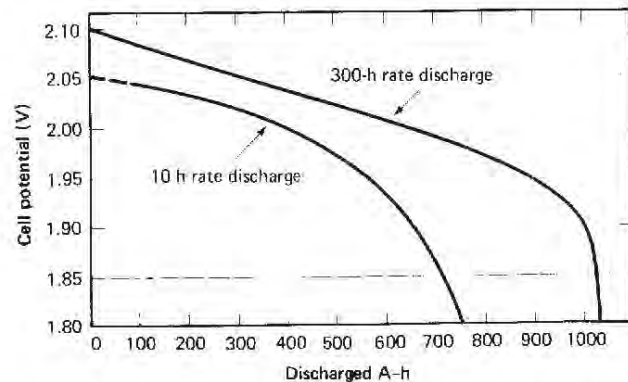


Figure 13.3. Constant-current discharge curves for a lead-acid battery at different discharge rates. (After Ref. 13.2.)

At moderate charge and discharge rates, about 80 to 85% of the charge put into a lead-acid battery can be recovered upon discharge. However, a large part of this inefficiency arises from gassing which occurs during charging. In the stand-alone photovoltaic mode, gassing is unlikely to occur during winter, when an appreciable amount of the load is being supplied from the battery. Hence, the charge storage efficiency in critical months will be much higher than the previous figure. Coulombic efficiencies as high as 95% have been quoted (Ref. 13.3).

13.3.3 Nickel-Cadmium Batteries

Nickel-cadmium batteries of the pocket-plate type have also been used in solar systems. Their major advantages compared to the lead-acid batteries described in Section 13.3.2 are:

1. Ability to be overcharged without damage
2. Ability to spend long periods only slightly charged without damage
3. Mechanically more rugged, making them more transportable
4. Ability to withstand freezing without damage

Their major disadvantages are:

1. Higher cost (about three times higher in large volume for a given storage capacity)
2. Low charge storage efficiency (55 to 60% for solar operation)
3. Significantly less capacity increase due to the low discharge rate in solar applications

At the present point in time, their advantages do not outweigh their disadvantages in most solar applications.

13.4 POWER CONTROL

A blocking diode is normally inserted between the battery and solar array to prevent the battery losing charge through the array at night. The voltage drop across the diode subtracts from the array voltage when it is supplying power to the battery. For silicon diodes, this

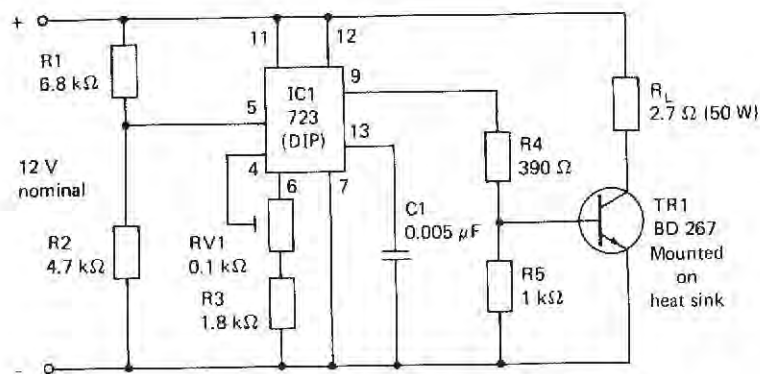


Figure 13.4. Shunt regulator for a 12-V/60-W solar array. (After Ref. 13.2.)

will be about 0.6 to 0.9 V but can be reduced to 0.3 V by the use of Schottky or germanium diodes.

To protect batteries from overcharging, some form of voltage regulation is required. For small systems, a simple linear shunt regulator can be used to dissipate the unwanted power. One possible design (Ref. 13.2) is shown in Fig. 13.4 for a 12-V system of up to 60 W of generating capacity. RV1 is adjusted to set the level at which the regulator cuts in. About 14.1 V is recommended. Any attempt to charge the battery voltage above this level will result in the charging current being shunted through R_L and TR1.

For large arrays, this technique is not feasible because of the large quantities of heat generated. A preferable method is to dissipate the extra energy as heat within the distributed solar cells. This can be accomplished by either short-circuiting or open-circuiting a portion of the solar array.

A schematic of a short-circuiting type of regulator is shown in Fig. 13.5. Transistors successively short out parallel sections of the array to maintain battery voltage below some desired limit. Although shorting an individual cell is completely acceptable, *problems can arise if a string of series-connected cells is shorted*. A cell generating below-average current can become reverse-biased and be made to dissipate virtually the entire peak module output, as discussed in Section 6.6.4. Field failures with this short-circuiting mode of regulation have been common. Consequently, it is not recommended unless special protective features such as bypass diodes have been incorporated into the modules that make up the array.

An alternative technique is to open-circuit the parallel sections. One approach using thyristors is shown in Fig. 13.6. Consid-

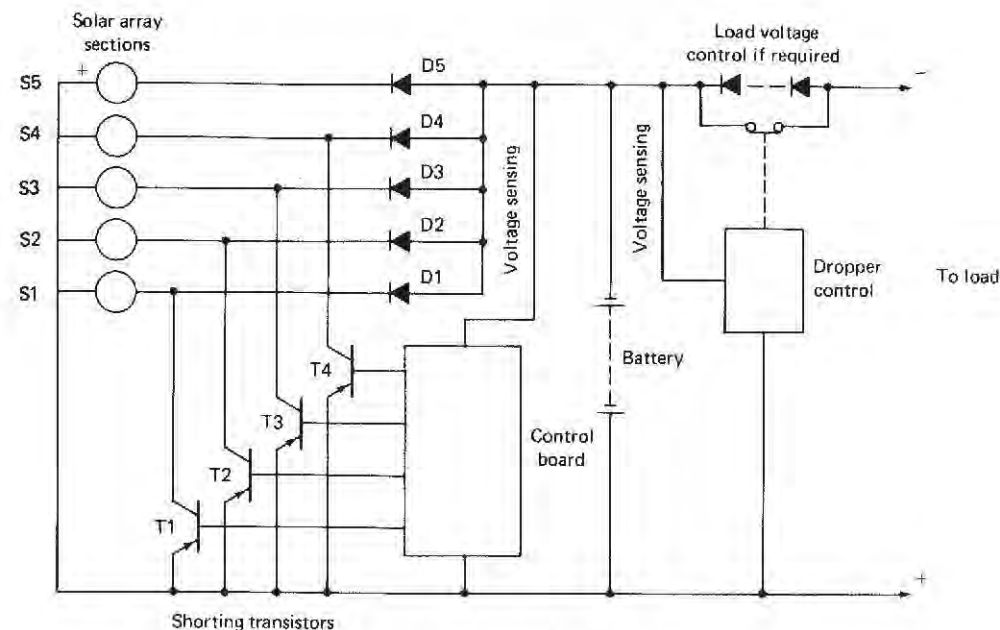


Figure 13.5. Possible technique for implementing a short-circuiting type of regulator for larger arrays. This type of regulation is not recommended unless protective features such as bypass diodes are incorporated into the array sections. (After Ref. 13.2.)

ering solar array group 1, pulses are directed to the base of either TR1 or TR4, depending on battery voltage. Pulses to TR1 ensure that TH1 is nonconducting, open-circuiting that section of the array. Pulses to TR4 switch the thyristor to its conducting state. In this state it fulfills the role of the normal blocking diode. Note that a degree of hysteresis is built into the voltage-sensing circuit to prevent instabilities. The battery voltage and array current obtained with such a system on a summer day when the battery is approaching a fully charged state is shown in Fig. 13.7.

13.5 SYSTEM SIZING

To size a solar system, it is essential to have accurate information about the load to be supplied and the best available radiation data for the intended site.

In cases such as microwave repeater stations, the load is easily determined since it is virtually constant. In other applications, such

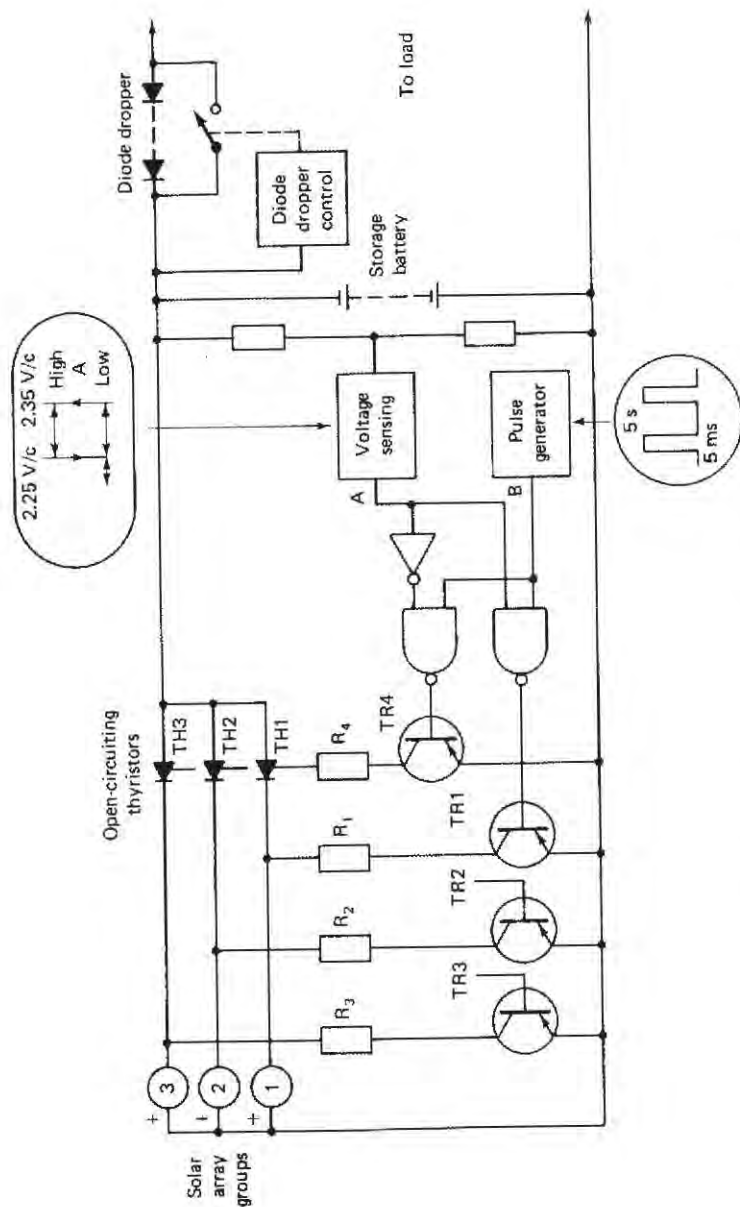


Figure 13.6. Thyristor open-circuiting mode of regulation. (After Ref. 13.2.)

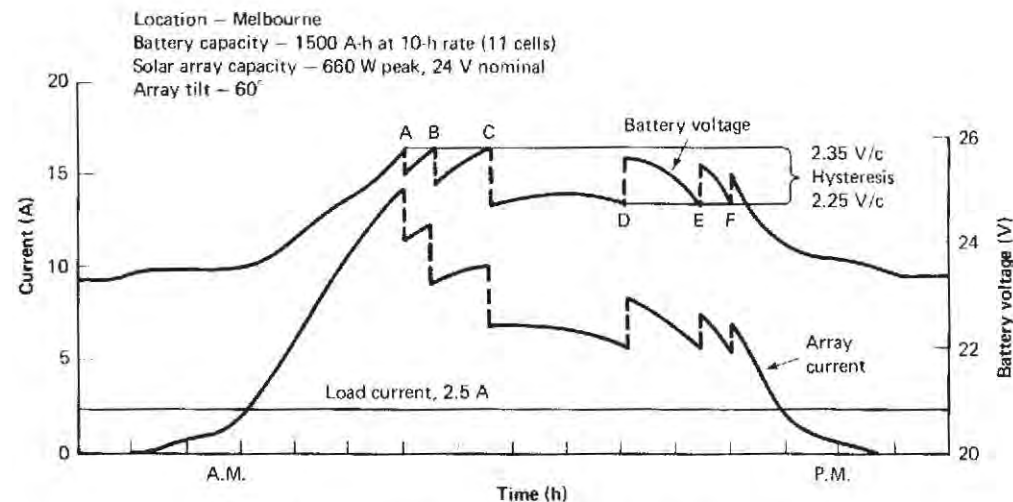


Figure 13.7. Operating characteristics of the method of regulation of Fig. 13.6. (After Ref. 13.2.)

as subscriber radio-telephone, the larger power demands in the transmitting mode makes the load dependent on the user call rate and hence highly unpredictable. Detailed radiation data are unlikely to be available for the type of remote locations where stand-alone solar systems are used. The best that can be done is to extrapolate from data recorded at stations in similar locations. A good source for data where more detailed information is not available is Ref. 13.4.

Solar cell suppliers and major users have developed computer programs for sizing photovoltaic systems. These programs can be quite sophisticated, taking into account such effects as the variation of solar and battery voltages upon temperature and capacity decrease in batteries with temperature. A simpler design technique will now be described which illustrates the concepts involved and which should be adequate where lack of data does not warrant a more detailed design.

The first step in this design procedure is to select the capacity required for the battery storage. The battery storage capacity can be regarded as serving two purposes. One is to provide a *reserve capacity* to cover an exceptionally long period without sunshine, or system failure. The other purpose is to provide seasonal storage (Ref. 13.3).

The amount of reserve capacity required depends on several factors. Climate is one. Sunny, arid regions require less than foggy coastal regions. The accessibility of the site, the regularity of system monitoring, and the consequences of system failure are other impor-

tant considerations. Normally, reserve capacity in the range 10 to 20 days is adequate, with 30 days a conservative extreme. In selecting a battery to give this capacity, consideration should be given to the effect of temperature and discharge rate on battery capacity.

Having selected the reserve capacity, the next step is to decide upon the depth of discharge acceptable for the system battery under normal seasonal fluctuations in solar energy input. Excessive depth of discharge will shorten lead-acid battery life as indicated in Section 13.3.2. Discharge to a depth of 50% of available capacity is the maximum desirable. On the other hand, designing for very shallow discharge will increase the size of the solar array required. As costs of modules decrease, optimum designs shift to shallower discharge depths.

Once the depth of discharge due to seasonal fluctuations is selected, the total battery capacity can be calculated. Since the reserve capacity (C_R) should be available even when the battery is at its lowest state of charge due to seasonal variations, the total capacity required is $C_R/(1 - d)$, where d is the fractional depth of discharge desired.

The size of the battery is now fixed. The next step is to select the size of solar array required. Current and voltage outputs are sized separately. The voltage output is selected to be large enough to allow the battery to be charged efficiently throughout the year. The current output is chosen to ensure that the battery does not discharge below the selected depth of discharge due to seasonal effects.

To proceed further, radiation data are required. Such data will normally be in the form of global radiation on a horizontal surface (R), possibly together with the diffuse radiation on such a surface (D). If the latter is not available, it is possible to provide a reasonable estimate using the technique described in Ref. 13.5. To convert the available data to radiation falling on an array of other than horizontal orientation, some assumptions must be made. Assuming daily data, the mean direct daily radiation on a horizontal plane (S) is given by

$$S = R - D \quad (13.1)$$

From Fig. 13.8(a), the direct component on a surface at an angle β to the horizontal is given by

$$S_\beta = S \frac{\sin(\alpha + \beta)}{\sin \alpha} \quad (13.2)$$

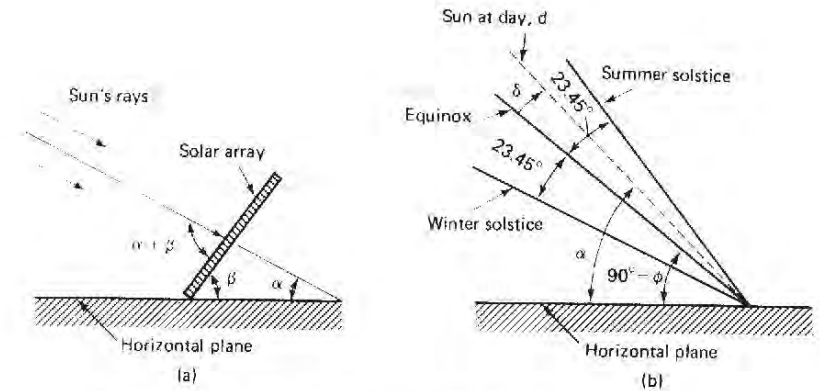


Figure 13.8. (a) Solar radiation at solar noon on a solar array tilted at angle β to the horizontal. Angle α is the altitude of the sun. (b) Relation between altitude of the sun (α), declination (δ), and latitude (ϕ).

where α is the noon altitude of the sun. From Fig. 13.8(b), α is given by

$$\alpha = 90^\circ - \phi \pm \delta \quad (13.3)$$

The plus sign applies for the northern hemisphere, the negative for the southern. Here ϕ is the latitude and δ the declination of the sun, given by

$$\delta = 23.45^\circ \sin \left[\frac{360}{365} (d - 81) \right] \quad (13.4)$$

where d is the number of days from the beginning of the year. Assuming that the diffuse radiation is independent of the array inclination, the total radiation on the array is given by (Ref. 13.2)

$$R_\beta = S \frac{\sin(\alpha + \beta)}{\sin \alpha} + D \quad (13.5)$$

Equation (13.5) is strictly correct only at midday, but it provides a reasonable approximation for converting daily horizontal radiation to radiation on an inclined surface. More elaborate approaches would give more accurate results (Ref. 13.5).

The design procedure can best be described by working through a concrete example. We will design a solar system for Mel-

bourne, Australia (latitude 37.8°S), capable of supplying 100 W continuously to a load at 24 V dc.

For this installation, a storage *reserve capacity* of 15 days is selected. Since the load requires 100 A-h/day, this corresponds to 1500 A-h of storage. Selecting 25% as the design depth of discharge due to seasonal fluctuations in solar intensity to prolong battery life gives a total installed capacity of 2000 A-h [$1500 \text{ A-h}/(1 - 0.25)$] at a discharge rate of 480 h (20 days).

The next stage in the design is to find the size of the solar module required to ensure that the batteries will not normally be discharged below 25% depth of discharge. The optimum angle of tilt of the fixed array will be the latitude angle plus 15 to 20° , say 60° for the present location. Once this angle to the horizontal, β , is selected, the raw radiation data are converted to radiation on a surface of this inclination. This is shown for Melbourne in Table 13.1. The average daily radiation on any array orientated 60° from the horizontal at this location is 21.0 MJ/m^2 . A lower bound for the current-generating capability of the array can be estimated by equating the input charge to the array over the year to the charge required by the load. This would represent the situation for an ideal system with infinite storage. In the present case, the load requires 100 A-h/day ($100 \text{ W} \div 24 \text{ V} \times 24 \text{ h}$). The average daily radiation intensity on the inclined surface is 21.0 MJ/m^2 , which, dividing by 3.6, converts to 5.83 kWh/m^2 or 583 mWh/cm^2 . This corresponds to 5.83 h of bright sunshine at peak sunshine intensity of 100 mW/cm^2 . Hence, the solar array peak current rating at 100 mW/cm^2 radiation intensity has to be at least 17.2 A ($100 \text{ A-h}/5.83 \text{ h}$).

Including the fact that not all charge supplied to the battery can be extracted from it but only an estimated 95% of charge for a battery below the gassing point, and allowing 10% degradation in performance for the average effect of dust accumulation, increases this estimate to 20.1 A ($17.2 \div 0.95 \div 0.90$).

An upper bound can be estimated by repeating this calculation using the radiation data for the worst month. If a system were designed in this way, the batteries would be very close to fully charged except during periods of inclement weather. For the present example the worst month is June, in which there is only the equivalent of 4.26 h of full sun radiation on the inclined surface. This gives an upper bound of 27.5 A ($20.1 \times 5.83 \text{ h} \div 4.26 \text{ h}$).

The optimum array peak current rating will lie somewhere between these extremes. It can be found by a trial-and-error calculation, which involves checking on the battery state of charge throughout the year. For the present example, the optimum peak current

Table 13.1 DATA FOR STAND-ALONE SOLAR SYSTEM DESIGN

System Data	Average daily radiation (mWh/cm^2)					Monthly ampere hours			Battery state	
	Global (R)	Diffuse (D)	On array*	Array†	Load‡	Difference	Start	Finish	% full charge	
Site: Melbourne, latitude 37.8°S Load: 100 W, 24 V Array inclination: 60° to horizontal Battery capacity: 2000 A-h Peak array current rating: 25 A										
Month										
Jan.	839	210	688	4559	3147	1412	2000	2000	100	
Feb.	708	149	648	3878	2842	1036	2000	2000	100	
Mar.	582	166	609	4036	3147	888	2000	2000	100	
Apr.	486	127	575	3687	3045	642	2000	2000	100	
May	297	98	463	3068	3147	-79	2000	1921	96	
June	246	79	426	2732	3045	-313	1921	1608	80	
July	277	82	462	3061	3147	-86	1608	1522	76	
Aug.	374	120	520	3446	3147	299	1522	1821	91	
Sept.	516	148	596	3822	3045	777	1821	2000	100	
Oct.	697	197	673	4459	3147	1312	2000	2000	100	
Nov.	732	241	637	4021	3045	976	2000	2000	100	
Dec.	890	214	701	4645	3147	1498	2000	2000	100	

*Calculated using Eq. (13.5).

†Calculated as:

Peak current rating $\times$ days in month $\times$ average daily radiation $\times$ charge efficiency $\times$ dirt accumulation factor/ 100 mW/cm^2

‡Including 3% discharge of peak battery capacity per 30-day month.

Source: Adapted from Ref. 13.2.

rating of the array is 25 A. The generated ampere-hours, consumed ampere-hours and battery state of charge as a function of time throughout the year is shown in Table 13.1. Note that the battery remains above the design figure of 75% charge throughout the year. If it dropped below this, the array size would have to be increased. If the state of charge always remained well above this figure, a more economical design would be to use a smaller array size. Although the results of calculations are shown for all months of the year, only those between which the monthly radiation is less than average need be considered. The calculation does indicate the large amount of power being thrown away in summer with this design approach. Figure 13.9 shows the battery state of charge as a function of time through the year for different array current ratings. It vividly illustrates the effect of a small increase in array size. For example, a 4% increase in array size would keep the batteries in a higher state of charge throughout the year than would doubling the storage capacity.

To complete the system sizing, the array voltage must be specified. For the design described above to be strictly valid, the array must be capable of supplying peak load current at the highest temperature it is likely to reach during normal operation, even with the batteries approaching full charge (~ 2.35 V per cell). For the design example, the array must be capable of supplying 25 A at a voltage of 29 V (12×2.35 V + 0.8 V for blocking diode) at its as-

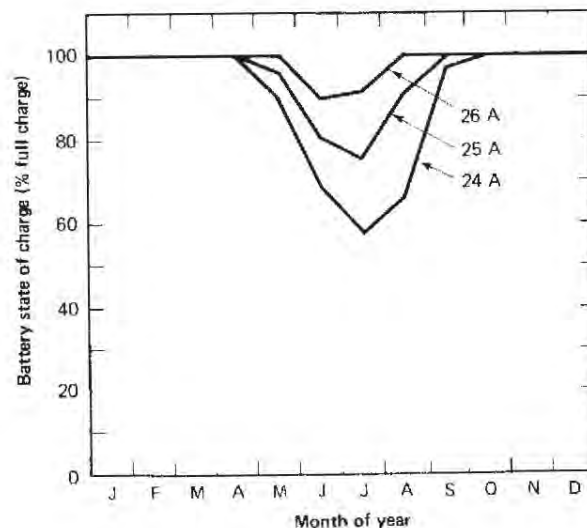


Figure 13.9. Battery state of charge for the design example in the text for three different array sizes.

sumed maximum temperature of 60°C . Therefore, the array must have a peak rating of 725 W at 60°C . Since the array power falls off at about 0.5% per $^{\circ}\text{C}$, this corresponds to a peak array rating of 879 W at the normal specification temperature of 25°C and incident power level of 100 mW/cm^2 .

However, this is a conservative design because of the large amounts of power that would be thrown away during summer. During the colder months, when the output of the module is most critical, weather data for Melbourne indicate that it would be unlikely for the ambient temperature to be above 20°C . For normal module designs, the cell temperature would be unlikely to exceed 44°C during these months. If an array output voltage of 29 V was specified at this temperature, the array would provide the calculated power during winter months. The output during summer would be less than calculated, although this may be no problem due to the large excess generated during these months.

The battery reaches its lowest state of charge in July, when the average temperature in Melbourne is about 10°C . Assuming that the battery operates at ambient temperature, this would require an increase in battery capacity to ensure that it still met the reserve-capacity requirement for this month. Assuming a 10% decrease in capacity at this temperature increases the required capacity to 2222 A-h at room temperature at a 480-h discharge rate. Both module and storage requirements may have to be modified to make them multiples of commercially available units. Sunnier regions of the world require smaller arrays to supply the same design load. For example, in some regions of Australia, arrays only two-thirds the size of the one calculated for Melbourne would supply this load (Ref. 13.2). A photograph of a solar power plant designed to supply loads of about this size is shown in Fig. 13.10. A shipping container is used to support the solar modules as well as to house the battery store, control electronics, and facilities for service crews.

To summarize the design procedure:

1. Determine load data.
2. Select battery size depending on latitude and any local climatic peculiarities.
3. Select an array inclination.
4. Estimate lower and upper bounds on array size from average and minimum monthly radiation falling on an array of the selected inclination.
5. Find the optimum array size to keep the batteries above a certain percentage charge throughout the year.



Figure 13.10. Solar power supply designed to provide approximately 100 to 150 W of electrical power continuously for a microwave repeater station. The shipping container supports the solar modules, as well as housing the storage batteries, control electronics, and facilities for servicing crews. (Photograph courtesy of Telecom Australia.)

6. Modify array inclination to find optimum if required.
7. Specify array voltage at the maximum operating temperature at which it is desired to supply full load current.

13.6 WATER PUMPING

Small-scale water pumping is an application well suited to the use of photovoltaics, for two reasons. First, solar arrays may be connected directly to the pump motor without requiring intermediate power conditioning or battery storage, giving a very simple, portable and potentially low maintenance system. Second, the requirement for pumped water decreases in periods of low solar insolation in many applications. This allows economical sizing of the system. Storage would be best implemented by storing pumped water.

One area where such small solar water-pumping units could make a big impact is in providing irrigation in less developed countries (Ref. 13.6). Irrigation can greatly improve the yield of a given

area of land with consequent benefits. A photovoltaic powered microirrigation system ($\sim 250W_p$) is well suited to the small plots cultivated by individual landholders. As it is unlikely that such landholders would be able to raise the necessary capital, an approach that has been advocated is to include such units in developmental aid programs (Ref. 13.6). This would serve two purposes. One would be to increase food supplies in these countries. The other would be to provide a substantial market for cells in the near term which would encourage their accelerated development.

13.7 SUMMARY

In principle, batteries produce the major maintenance requirements of stand-alone photovoltaic systems, requiring an annual or semi-annual topping up of electrolyte. However, the system must be carefully designed to produce maximum battery life. Overcharging of lead-acid batteries must be prevented, as must undercharging, which leaves the batteries with low stored charge over long periods.

Continuing decreases in the power demands of electronic communications equipment and in the costs of solar cells have made telecommunications the first major commercial terrestrial application for these cells. Stand-alone systems similar to those described in this chapter have been deployed in applications including microwave repeater stations, navigational aids, meteorological stations, and corrosion protection.

In the design of stand-alone systems, a large storage capacity is used to provide high reliability. The solar array is sized to ensure that this battery retains a reasonable percentage of full charge over the lower insolation winter months. In this design mode, the solar system does not produce the maximum possible power output over the year. For the most ideal stand-alone installations, the peak rating of the array must be about five times the average power the system is to provide. In marginal locations, this can increase by a factor of 2 or more.

EXERCISES

- 13.1. For the design example of Table 13.1, compare the typical daily cyclic variation in battery state of charge with the seasonal variation.
- 13.2. For a location at latitude 34°N , find the angle of solar array tilt that will maximize the system output for November, using the approximate

method outlined in the text. The average global radiation at this location on a horizontal surface in November is $12 \text{ MJ/m}^2/\text{day}$, and the corresponding figure for diffuse radiation is $4.1 \text{ MJ/m}^2/\text{day}$.

- 13.3. Design a stand-alone photovoltaic system for a location at latitude 23°N . The system is to supply a constant load of 250 W at 48 V dc. Starting at January, the global figures for radiation on a horizontal surface for the 12 months of the year are (the numbers in parentheses are the corresponding figures for diffuse radiation): 15.5 (3.2), 17.2 (4.2), 21.6 (4.0), 23.3 (6.0), 24.9 (7.0), 24.1 (8.8), 23.8 (8.9), 22.9 (8.1), 20.7 (7.3), 18.9 (4.8), 15.6 (4.7), and $14.5 (3.8) \text{ MJ/m}^2/\text{day}$, respectively.

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Chapter 14

RESIDENTIAL AND CENTRALIZED PHOTOVOLTAIC POWER SYSTEMS

14.1 INTRODUCTION

In this, the final chapter of this book, issues surrounding potential long-term applications of solar cells are raised. Two areas where photovoltaics could produce significant contributions to world energy demands is in supplying residential power and in generating electricity in large, centralized power plants. Because of the massive scaling up of cell production that generation at this level would entail and the finite diffusion rates of a new technology into commercial use, it is unlikely that this contribution will be more than a few percent prior to the turn of the century. This does not mean that there will not be systems of this type operating economically well before this date.

In large-scale production, economic analyses indicate that most of the advanced silicon technologies described in Chapter 7 can produce solar cell modules which can be sold at a cost that makes them competitive for supplying residential power. The demands placed on module costs for photovoltaics to compete in the form of large, centralized power plants are about twice as severe. As discussed in Chap-

ter 10, thin-film photovoltaic devices have the best prospects for attaining the ultimate low in module costs.

14.2 RESIDENTIAL SYSTEMS

14.2.1 Storage Options

In Chapter 13, the use of photovoltaics was described in stand-alone configurations for remote areas. However attractive it might seem to be independent of the electricity supply authority, a stand-alone system is not viable for areas where grid power is available. Substantial reductions in the cost of electrical energy storage on a small scale would be required. This may be possible with systems such as the redox system described in Chapter 12.

Without an inexpensive method of storing electricity, the most viable approach is to connect the photovoltaic system to the electricity supply grid. This eliminates the need for *long-term* energy storage. Several different system configurations are possible in this grid-connected mode. An integral part of each of these systems is an inverter to convert solar cell dc output to alternating form.

Even though the grid may be used as a long-term storage medium, the question as to whether *short-term* storage on site is desirable has to be addressed. This storage would help tide over the system overnight or through short periods of bad weather. For prolonged periods of poor weather, the presence of short-term storage would allow the grid to supply power to the residence at its convenience. A system without on-site storage is also workable, particularly if the utility is prepared to buy back excess electricity generated. The optimum size of the array in this case increases for increasing buy-back rates.

From the householder's point of view, the optimum system depends on the relative costs of solar and storage systems, plus the utility rate structure. Large differentials in rates depending on the time of day would encourage increased storage, whereas a willingness on the utility's part to buy back excess electricity generated by the residence at a reasonable fraction of selling rates would decrease the optimum storage size. Battery storage is the most promising storage technique. The major disadvantages are the potential hazards associated with batteries in residential settings and problems posed by the regular maintenance the batteries would require. Nonetheless, with suitable venting and electronic protection of the battery, such storage is feasible (Ref. 14.1). A possible battery-pack configuration is shown

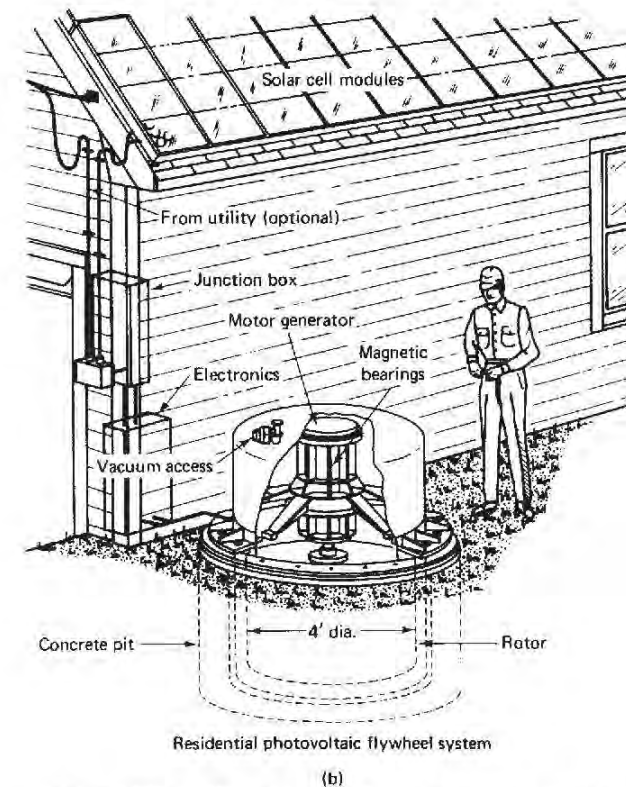
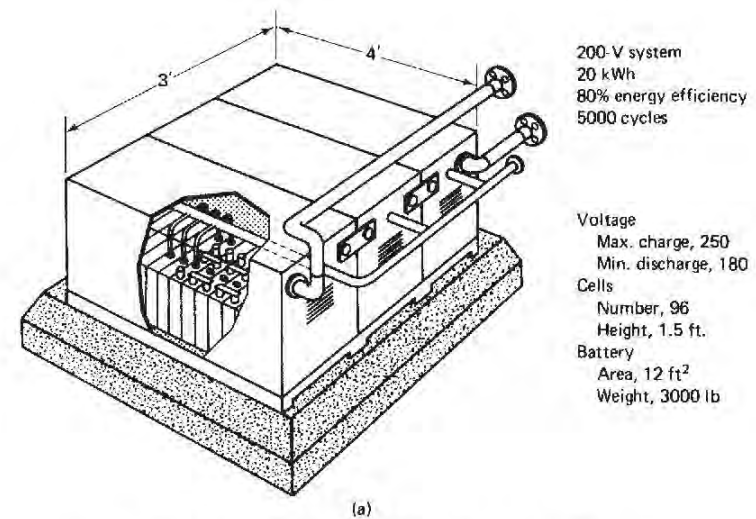


Figure 14.1. Energy storage concepts for residential systems:

- (a) Possible battery configuration. (After Ref. 14.1.)
(b) Flywheel storage. (After Ref. 14.2, © 1980 IEEE.)

in Fig. 14.1(a). A redox system as described in Chapter 12 would have several advantages if successfully developed. Flywheel storage has also been considered (Ref. 14.2). An indication of the size of the unit required is given in Fig. 14.1(b).

14.2.2 Module Mounting

Studies indicate that the cheapest method of mounting the solar modules is to integrate them into the roofing as indicated in Fig. 14.2(a) so that they form the dual role of generating electricity and providing protection from the elements (Ref. 14.3). Retrofitted modules probably would be mounted in the stand-off configuration of Fig. 14.2(b). Although installation costs would be similar for both configurations, there would be an additional credit for normal roofing materials displaced by the solar modules in the integral approach.

Optimum module size for this application has been estimated to be about 0.8×2.5 m with a corresponding module weight of about 25 kg (Ref. 14.3). Wiring costs decrease with increasing array voltage output, although this dependence is not strong for voltages over 100 V dc (Ref. 14.3). The reference cited indicates that aesthetic considerations favor rectangular modules with aspect ratios about 2:1, of a dark earth-tone color, and having a matt finish. Shingle modules [Fig. 14.2(c)] may also be attractive if inexpensive interconnection techniques can be developed (Ref. 14.4).

14.2.3 Thermal Generation

A large portion of the residential use of energy will be in the form of low-grade heat for hot-water systems and space heating. The question arises as to how this can be best supplied in a system that includes photovoltaic cells. Three possible alternatives are to use the photovoltaic modules to provide both electrical and thermal requirements of the residence, to use a separate solar thermal collector for supplying the thermal loads, or to use combined photovoltaic/thermal modules or a *total energy system*.

Although conceptually appealing, the total energy system with photovoltaic and thermal functions incorporated into the same module has a number of disadvantages. The solar cells of necessity will operate at higher temperatures and hence lower efficiency. The thermal collector will also operate at lower efficiency, because the cells will be extracting some of the available energy. The ratio of ther-

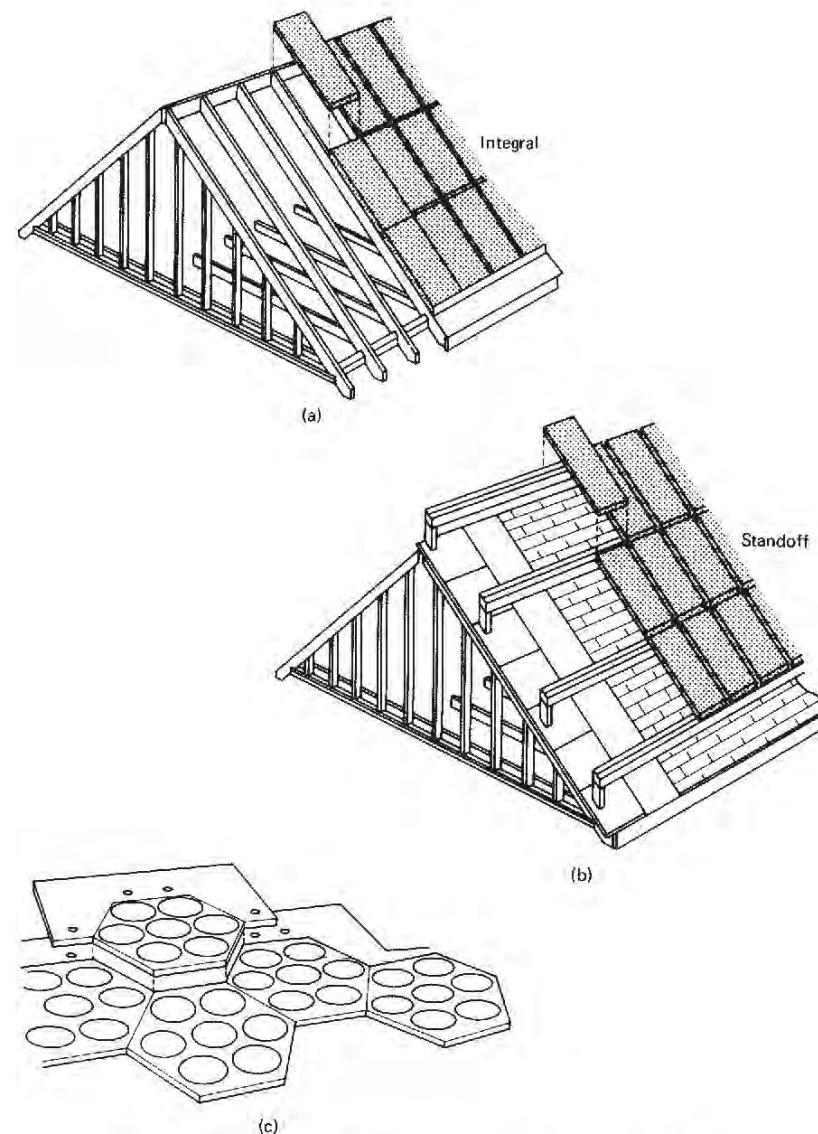


Figure 14.2. Possible mounting schemes for rooftop solar cell modules:

- (a) Integral. (After Ref. 14.3.)
- (b) Standoff. (After Ref. 14.3.)
- (c) Shingle.

mal to electrical energy generated generally will not be the same as that required by the residence. Studies indicate that residential total energy systems seldom are likely to be more cost effective than systems with optimum areas of photovoltaic and thermal modules (Ref. 14.5).

The choice between this system and an all-photovoltaic system depends on whether the simplicity of the latter approach overcomes the inefficiency inherent in converting sunlight to electricity and then to heat. At low photovoltaic module costs, this can be the case.

14.2.4 System Configurations

Several possible system configurations are shown in Fig. 14.3. In the first, shown in Fig. 14.3(a), battery storage is used in conjunction with a regulator (to prevent battery overcharging) connected between the module and the battery. In this connection, the input voltage to the inverter is the battery voltage. Fig. 14.3(b) shows a potentially more efficient variation where only that portion of the output used to charge the battery is diverted through the regulator branch. Without battery storage as in Fig. 14.3(c), the output of the module is connected to the inverter, which can be designed to ensure that the module delivers power at its maximum power point. Finally, Fig. 14.3(d) shows how a thermal collector could be integrated into the previous system. In each case, the ac output of the inverter is synchronized to the utility input.

14.2.5 Demonstration Program

In late 1979, the U.S. Department of Energy initiated a Solar Photovoltaic Residential Project. The purpose was to clarify the issues involved in the residential use of photovoltaics in grid-connected areas and to facilitate commercialization of appropriate systems. As originally outlined (Ref. 14.6), the project was to be completed in 1988, involving three major stages as illustrated in Fig. 14.4.

The first stage involved the construction of regional experiment stations in representative areas of the country. These stations were to test prototype systems designed and built by industry. These prototype systems were roof-only systems installed at the stations, delivering the estimated electrical and thermal residential requirements. The actual use of these quantities by residences in the neighborhood of the station was monitored at the same time as the performance of the prototypes to check compatibility.

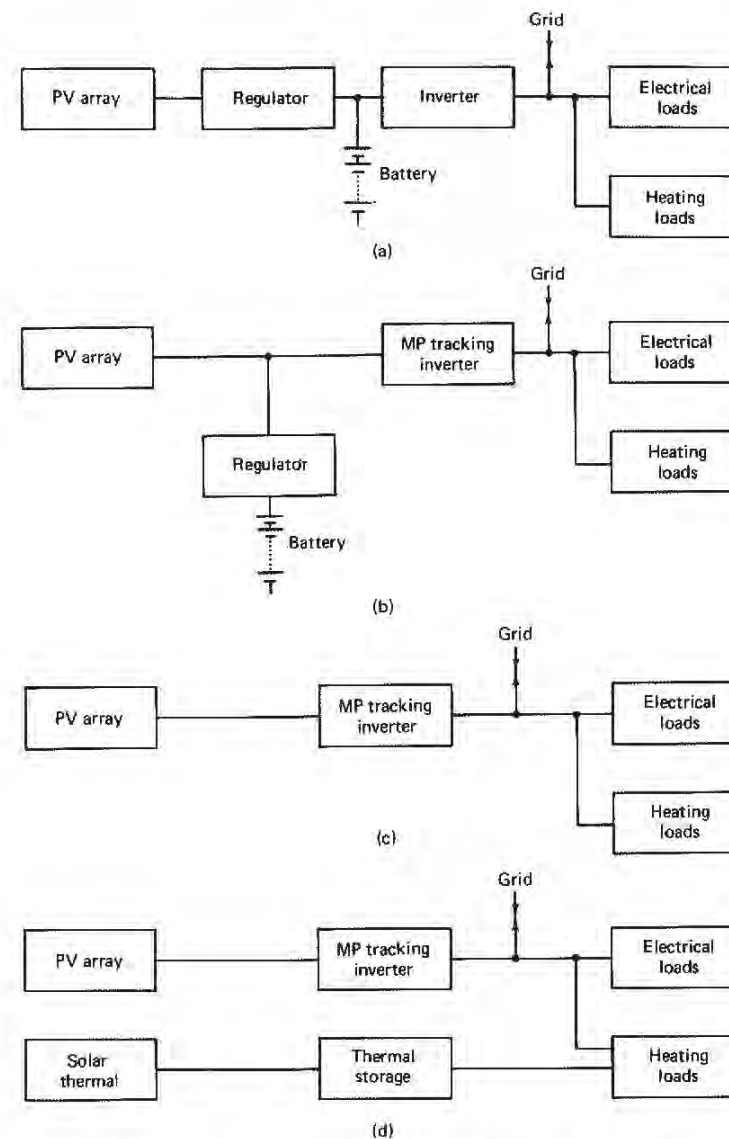


Figure 14.3. Possible interconnection scheme for photovoltaic residential systems. See the text for details..

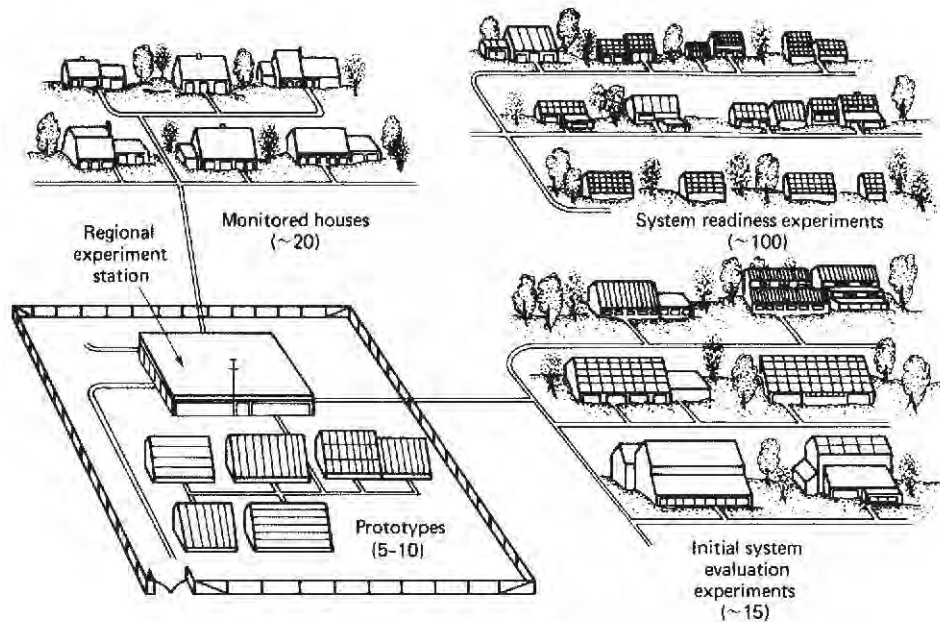


Figure 14.4. Outline of the DOE Residential Program, ranging from initial prototype testing in regional experiment stations to the deployment of a large number of solar-cell-powered residences in the commercial readiness experiments. (After Ref. 14.6.)

In the next stage, refinements of successful prototypes were to be tested by installation at a small number of occupied residences near the experiment stations. These initial system-evaluation experiments were concerned not only with physical performance but also with occupant and institutional responses.

In the final phase, scheduled to start in 1984, system readiness experiments were to be conducted independently of the regional experiment stations. In this phase, clusters of about 100 solar-powered residences were to be built to confront, head-on, the institutional and engineering issues resulting from the widespread use of photovoltaics in the residential sector (Ref. 14.7).

14.3 CENTRAL POWER PLANTS

14.3.1 General Considerations

The ultimate goal for photovoltaics is to compete in an economic sense with conventional methods of generating large quantities

of electricity in a centralized power plant. Several studies have identified essential properties for this to occur.

One obvious condition is that the solar modules must be inexpensive, somewhat less expensive than for residential use. A less obvious condition is that the modules have to be efficient. A solar array efficiency of at least 10% is desirable. Lower efficiencies increase the area of the array that is required to produce a given output. This increases such costs as site preparation, the cost of support structures, installation costs, and maintenance costs. These costs, as well as those of power conditioning equipment, are often referred to as *balance-of-system costs*. Careful consideration has to be given to keeping balance-of-system costs to a minimum.

Studies indicate that the optimum module size for large-scale application is of the order of 1.2×2.4 m (Ref. 14.8). A large number of different approaches have been considered for support structures. The most severe load placed on this support structure is wind loading, with the design wind loading largely determining its cost. The low profile of photovoltaic arrays and the aerodynamic shielding provided by adjacent rows in an array field or by a surrounding fence act to greatly reduce these loads. Preliminary results show that the wooden-pole support system of Fig. 14.5(a) looks attractive for smaller installations, and that the concrete-truss support system of Fig. 14.5(b) becomes competitive for large installations (Ref. 14.9).

It is unlikely that a terrestrial photovoltaic system would be used as the *sole* source of electricity in any grid network. Either the costs of long-term energy storage would be prohibitive, or the array would have to be grossly oversized so that it could generate the required energy even in cloudy weather. It would be possible to alleviate this difficulty by using the photovoltaic system in conjunction with a nonsolar plant of lower power rating together with relatively short term storage. The most likely role that photovoltaics would play in a large network in the foreseeable future is a fuel-displacement role. Since such a network already has considerable flexibility in meeting a time-varying demand, photovoltaics can be used *without storage*, provided that they contribute less than about 10% of the total generating capacity of the network.

Because of the diffuse nature of solar radiation, large land areas are required to generate substantial amounts of energy using photovoltaics. Some perspective to the question of land use is given by considering the percentage of land required to be covered by photovoltaics to generate *all* the energy requirements of selected countries. The results of such a calculation are shown in Table 14.1. Although some European countries have poor results, for obvious reasons, in

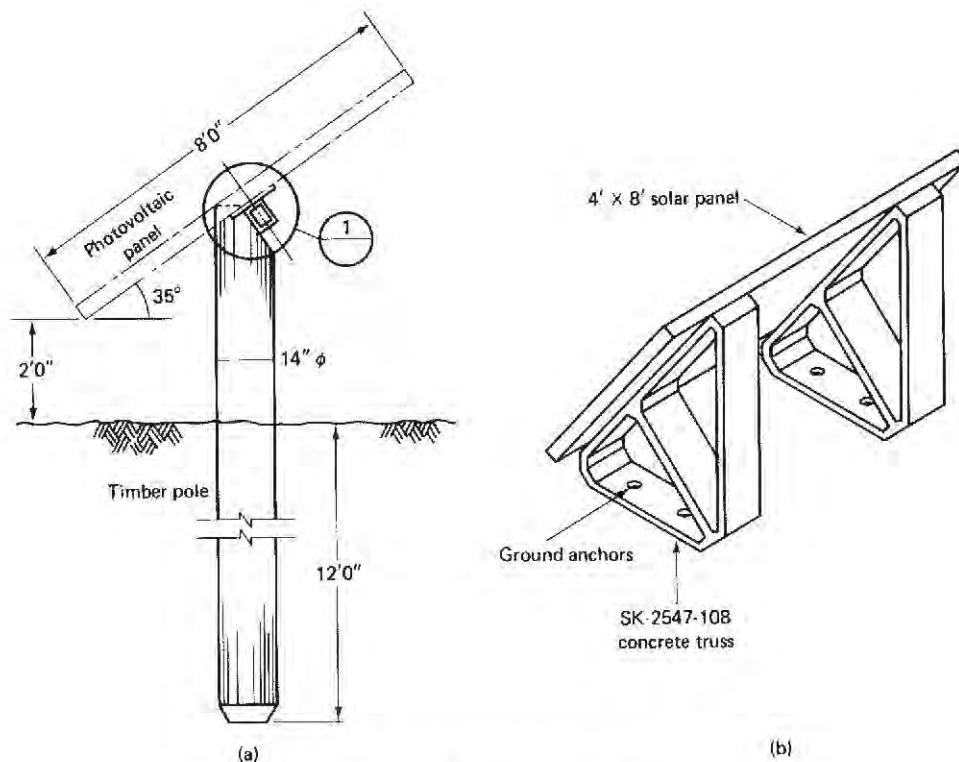


Figure 14.5. Alternative approaches for supporting solar cell modules in large field installations:

- (a) Wood pole/torsion tube system.
 - (b) Concrete truss system.
- (After Ref. 14.9, © 1980 IEEE.)

many countries such as the United States the required land area is less than that presently covered by man-made structures such as buildings and roads. Although an enormous task, the installation of a photovoltaic system over several decades capable of supplying all the world's energy requirements obviously is not beyond present engineering realities.

14.3.2 Operating Mode

Figure 14.6(a) shows a plot of the power demand placed on a hypothetical electricity authority during a typical day. Also shown is the effect that a solar plant incorporated into the authority's network

Table 14.1. PERCENTAGE OF LAND AREA REQUIRED TO GENERATE ALL THE ENERGY REQUIREMENTS OF THE COUNTRIES SHOWN IN 1970 WITH PHOTOVOLTAICS OF 10% EFFICIENCY

Australia	0.03
Canada	0.20
Denmark	4.5
Eire	1
France	3.5
Israel	2.5
Italy	4
Netherlands	15
Norway	0.50
South Africa	0.25
Spain	1
Sweden	0.75
United Kingdom	8
United States	1.5
West Germany	8

Source: After D. O. Hall, "Will Photosynthesis Solve the Energy Problem?" in *Solar Power and Fuels*, ed. J. R. Bolton (New York: Academic Press, 1977), p. 36.

would have upon the load to be supplied by the remainder of the system. In a system where the load demand peaks in the evening, the effect of the solar plant is to sharpen the peak and broaden the trough of the daily demand curve.

As previously mentioned, with small penetration of the supply network, no storage is necessary with photovoltaics. The grid will be capable of absorbing the fluctuating solar supply just as it now absorbs fluctuating demand. Without storage, the solar plant would act as a fuel saver, decreasing the time that *intermediate* and *peaking* generating equipment would have to operate. However, the tendency to sharpen peaks in the daily demand curve improves the effectiveness of a given amount of energy storage in leveling demand, as shown schematically in Fig. 14.6(b) and (c). Thus, even though the energy storage is charged primarily by the *base-load* equipment in the network rather than the solar plant as indicated in Fig. 14.6(b), there is a synergistic effect between solar plant and energy storage. The presence of one improves the performance and viability of the other. It follows that networks installing energy storage now for operation with coal- and nuclear-base-load plants will be in the best position to implement solar plants as they become available.

Another important concept in central power plant operation is the *capacity credit* to be given to solar plants. It might be argued

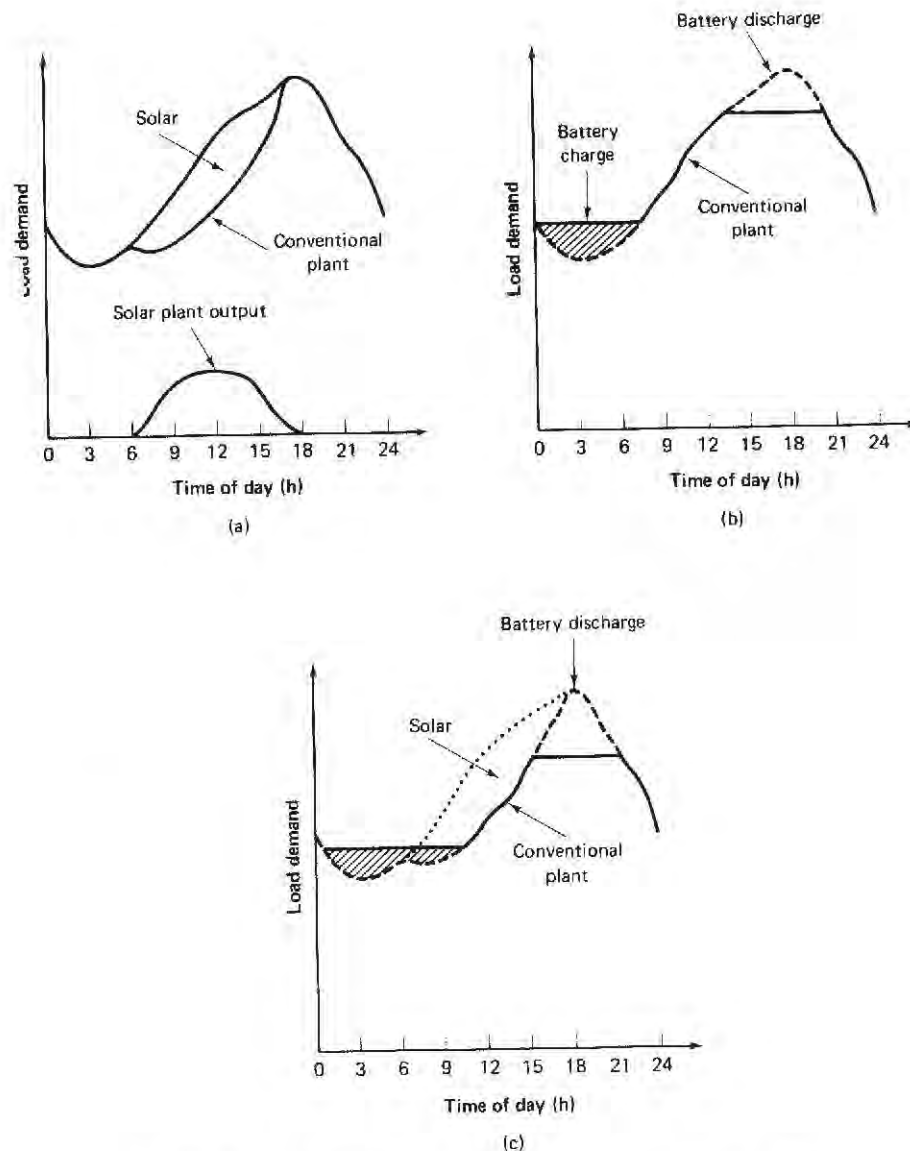


Figure 14.6. (a) Typical daily load demand profile, showing the effect of a small contribution from a solar plant. (b) Use of energy storage to trim the peak in the load demand profile for a system without solar input. (c) As for part (b) except with solar input. (After Ref. 14.10, © 1978 IEEE.)

that no credit could be given to a photovoltaic plant because its output would be very low on cloudy days and backup capacity would be required to cover these days. The actual situation is more complex. Conventional equipment can also be forced out of service unexpectedly. A method used to calculate the capacity of a system is to specify the level of reliability in meeting demand that is required and to calculate the maximum load that can be met to this level of reliability.

Figure 14.7 shows the result for a particular grid network of such a calculation for a base system without photovoltaics, for a system that includes 500 MW_p of photovoltaics, and for a system with the latter as well as 2000 MWh of battery storage (Ref. 14.10). In this system the capacity credit for photovoltaics works out at about one-third of peak capacity. Combined with the battery storage, the capacity credit increases to 580 MW. In this example, the maximum power demand occurs at about 6 P.M. in summer as is typical of many U.S. utilities. If the peak occurs closer to midday, the capacity credit for photovoltaics alone would be even a higher fraction of peak capacity. On the other hand, for systems where the peak load occurs outside the daylight hours (e.g., winter evenings), the capacity credit would be much smaller.

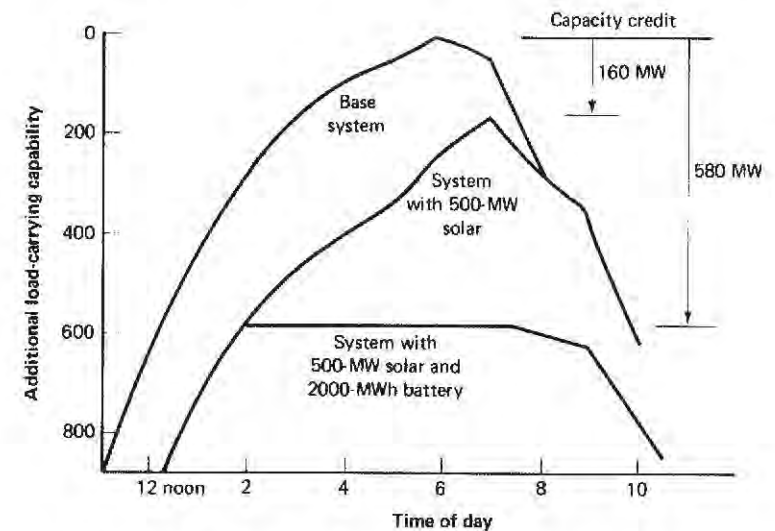


Figure 14.7. Result of a computer simulation of the capacity credit to be attributed to a solar photovoltaic plant. In the example shown, the capacity credit is about one-third the peak rating of the plant. Battery storage greatly increases the capacity credit. (After Ref. 14.10, © 1978 IEEE.)

No book on photovoltaics would be complete without some mention of the imaginative concept of using large solar cell arrays in space to capture sunlight and beam energy back to earth as microwaves, as illustrated in Fig. 14.8. The solar station would be placed in geosynchronous orbit around the earth at an altitude that is large compared to the earth's radius. This would ensure that the earth did not shadow the array except for periods of about 1 h around local midnight for the weeks surrounding the equinoxes. A more detailed discussion is given in Ref. 14.11.

The major advantage of the system is that sunlight would be available continuously except for the periods mentioned above. Storage is not required and the system could be used in a base-load role. Other advantages include the higher sunlight intensities in space and the fact it is relatively easy to ensure the arrays are always nearly normal to the sun's rays. A solar array of a given peak rating could generate five to eight times the energy of a similarly sized array at a sunny location on earth. This factor would be reduced by the losses associated with the transmission of the collected energy to earth.

The major disadvantages are strategic vulnerability and high balance-of-system costs. As well as the immense problems associated with constructing such an array in space and maintaining it, a collecting receiver of significant size has to be constructed on earth. The possible environmental effects of a microwave beam of the required size and intensity also deserve careful scrutiny.

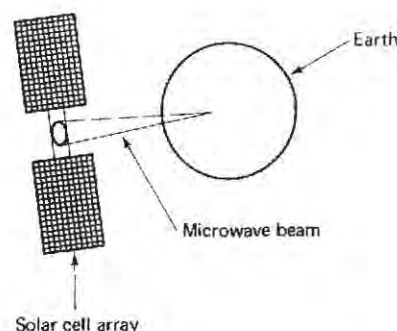


Figure 14.8. Satellite solar power station. The energy collected is beamed back to earth as microwaves.

In this, the final chapter of this book, issues surrounding two proposed long-term applications of solar cells have been considered. The costs required for cells to be viable in these applications are, without a doubt, within the realms of technical feasibility.

Residential use of photovoltaics in grid-connected areas becomes possible at higher module costs than central power generation using photovoltaics because the appropriate point of view to calculate costs in the former case is that of the householder. From the technical point of view, several solar cell technologies have been recognized which can produce cells at the costs required for this application. The major obstacles to the residential use of photovoltaics are not technical but institutional. These issues relate to building codes, integration with utilities, financing of the solar arrays, and so on.

Photovoltaics are unlikely to be used in a stand-alone mode in a central power-generating role because of the excessive energy storage required. With small but significant contributions to the grid-generated power, energy storage is not an essential partner to a photovoltaic plant. The two elements do complement each other to some extent, the presence of either making the other more viable. In conjunction with a nonsolar backup system and moderate amounts of storage, ultimately photovoltaic plants would be capable of generating the majority of power supplied by a grid network.

Thin-film technology is available at the present point in time for producing solar cells at the costs *per unit area* required for this central power-generating role. The improvement required is in the power output per unit area obtained from such cells. Expressed in a different way, thin-film amorphous silicon cells became commercially available in 1980 whose performance equaled that of high-quality single-crystal cells for the indoor applications for which they were designed. The challenge facing photovoltaics is to produce thin-film cells that can duplicate this feat *outdoors*.

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Appendix

A

PHYSICAL CONSTANTS

q	electronic charge = 1.602×10^{-19} coulomb
m_0	electronic rest mass = 9.108×10^{-28} g = 9.108×10^{-31} kg
c	velocity of light in vacuum = 2.998×10^{10} cm/s = 2.998×10^8 m/s
ϵ_0	permittivity of free space = 8.854×10^{-14} farad/cm = 8.854×10^{-12} farad/m
h	Planck's constant = 6.625×10^{-27} erg-s = 6.625×10^{-34} joule-s
k	Boltzmann's constant = 1.380×10^{-16} erg/K = 1.380×10^{-23} joule/K
$\frac{kT}{q}$	thermal voltage = 0.02586 V (at 300 K)
λ_0	wavelength in vacuum associated with photon of 1-eV energy = 1.239 μ m

PREFIXES

milli (m) = 10^{-3}	kilo (k) = 10^3
micro (μ) = 10^{-6}	mega (M) = 10^6
nano (n) = 10^{-9}	giga (G) = 10^9
pico (p) = 10^{-12}	

B

SELECTED PROPERTIES
OF SILICON (AT 300 K)

E_g	energy gap = 1.1 eV (see Table 3.1)
N_C	effective density of states in conduction band = $3 \times 10^{19} \text{ cm}^{-3} = 3 \times 10^{25} \text{ m}^{-3}$
N_V	effective density of states in valence band = $1 \times 10^{19} \text{ cm}^{-3} = 1 \times 10^{25} \text{ m}^{-3}$
n_i	intrinsic concentration = $1.5 \times 10^{10} \text{ cm}^{-3} = 1.5 \times 10^{16} \text{ m}^{-3}$
ϵ_r	relative permittivity = 11.7
$\hat{n}$	refractive index = 3.5 (at a 1.1- μm wavelength) (see Fig. 3.1)
μ_e	electron mobility $\leq 1350 \text{ cm}^2/\text{V-s} \leq 0.135 \text{ m}^2/\text{V-s}$ [see Eq. (2.36)]
μ_h	hole mobility $\leq 480 \text{ cm}^2/\text{V-s} \leq 0.048 \text{ m}^2/\text{V-s}$ [see Eq. (2.36)]
D_e	electron diffusion coefficient = $0.02586 \mu_e$
D_h	hole diffusion coefficient = $0.02586 \mu_h$
ρ	electrical resistivity [see Eq. (2.35)] density = $2.33 \text{ g/cm}^3 = 2330 \text{ kg/m}^3$

C

LIST OF SYMBOLS

E	electric field strength
α	absorption coefficient
ϵ	dielectric constant
ϕ	work function
ϕ_B	barrier height
λ	wavelength
μ	mobility
η	efficiency
ρ	space-charge density; resistivity; sheet resistivity; specific contact resistance
σ	conductivity
τ	lifetime
ψ_0	built-in potential
χ	electron affinity
A	cross-sectional area
c	velocity of light in vacuum

D	diffusion coefficient
E	energy
E_c, E_v	energies of conduction- and valance-band edges
f_c	collection probability of light-generated carriers
E_F	Fermi level
FF	solar cell fill factor
G	generation rate of electron-hole pairs
h	Planck's constant
I	current; intensity
I_0	diode saturation current
I_{sc}	short-circuit current
J	current density
J_e, J_h	electron and hole current densities
k	Boltzmann's constant
$\hat{k}$	extinction coefficient
L_e, L_h	diffusion length for electrons and holes
m_0	electronic rest mass
m_e^*, m_h^*	effective mass of electrons and holes
n	electron concentration
n_{n0}, n_{p0}	thermal equilibrium concentration of electrons in n -type and p -type semiconductors
$\hat{n}_c$	refractive index
$\hat{n}$	real part of refractive index
n_i	intrinsic concentration
N_C, N_V	effective densities of states in conduction and valance bands
N_A, N_D	densities of acceptors and donors
p	hole concentration; crystal momentum; fractional power loss
p_{n0}, p_{p0}	thermal equilibrium concentration of holes in n -type and p -type semiconductors
q	electronic charge
R	resistance
t	time
T	temperature
U	net recombination rate
V	voltage; potential
V_{oc}	open-circuit voltage

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