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# Contribution of Spectrally Selective Reflector Surface to Heat Reduction in Silicon Concentrator Solar Cells

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## 1. Introduction

Energy has been playing an important role for civilization. In the early ages, wood was the main source of energy. Industrialization and modernization which started around two hundred years ago were mainly based on fossil fuels and even now they are being used on a large scale. Huge demand of such energies has caused environmental problems and rises in coal and oil prices as well. With ever expanding cities consuming more and more energy, the fuel reserves for example oil, gas, coal, etc., throughout the world may not be able to match the demand. There is a drive towards biofuels but unless the world's food energy needs are addressed, the viability of such fuels will remain a mirage for many decades. This therefore calls for alternative sources of energy such as those employing wind, photovoltaic, biomass, geothermal and wave power technology. The sun alone is continually releasing an enormous amount of radiant energy into the solar system. The Earth receives a tiny fraction of this energy; yet, an average of 1367 watts reaches each square meter of the outer edge of the Earth's atmosphere. The atmosphere absorbs and reflects some of this radiation, including most X-rays and ultraviolet rays but still, the amount of solar energy received by the surface of the earth per minute is greater than the energy utilization by the entire population in one year (Sen, 2004).

### 1.1 Solar radiation

Electromagnetic radiation occurs over widely different wavelength ranges: from cosmic, gamma, X-rays to long radio waves. Sunlight is electromagnetic radiation in the spectral range of 0.3 μm to 4 μm with its maximum intensity around 0.5 μm. This spectrum corresponds to an effective blackbody temperature of about 5800 K (McVeigh, 1977, Sze, 1991). The wavelengths for many solar energy applications are found in the range from the ultra violet at 0.3 μm to the infrared at 50 μm covering the solar spectral range and the spectral range of the thermal radiation emitted from a surface having a temperature of about ambient up to 100°C (2 to 50 μm).

Terrestrial solar radiation is a low-intensity, variable energy source reaching a maximum of about 1000 W/m². The intensity of the terrestrial spectrum depends on the distance

travelled through the atmosphere. Outside the atmosphere the spectrum is denoted air mass zero, AM 0, while the radiation that travels through the atmosphere is AM X where

$$X = \frac{1}{\cos\theta_z} \tag{1.1}$$

$\theta_z$ is the angle of incidence with respect to zenith (Blatt, 1991). Equation 1.1 is valid only for zenith angles less than 70° (Kreith and Kreider, 1978). At greater zenith angles, the accuracy degrades rapidly, with X becoming infinite at the horizon. Figure 1.1 shows a normalized solar spectrum for air mass 1.5 (AM 1.5). It represents a satisfactory energy-weighted average for terrestrial applications. It has several local minima, which are caused by absorption in the atmosphere mainly by water vapour, carbon dioxide and ozone (Duffie and Beckman, 1991). AM 1.5 has been used later in this chapter to calculate average solar values of reflectance given that it is advisable to compare different optical properties in devices within certain spectral regions. These regions can be defined for certain environments, eye adaptation abilities, material temperatures etc. An expression that gives the average, $H_\xi$, for the measured reflectance, transmittance, absorptance or emittance of a device $H(\lambda)$, has been defined as (Mwamburi & Wäckelgård,, 2000):

$$H_\xi = \frac{\int_a^b H(\lambda) \cdot \phi_\xi(\lambda) d\lambda}{\int_a^b \phi_\xi(\lambda) d\lambda} \tag{1.2}$$

where $\phi_\xi(\lambda)$ is the source function of a specified property, $\xi$, which can be the solar irradiance on earth at a certain level and angle, the range of the human eye sensitivity or the thermal spectrum of a black body. In this work, $\phi_\xi(\lambda)$ is the solar irradiance (AM 1.5) and $H(\lambda)$ is the reflectance in some specified wavelength range.
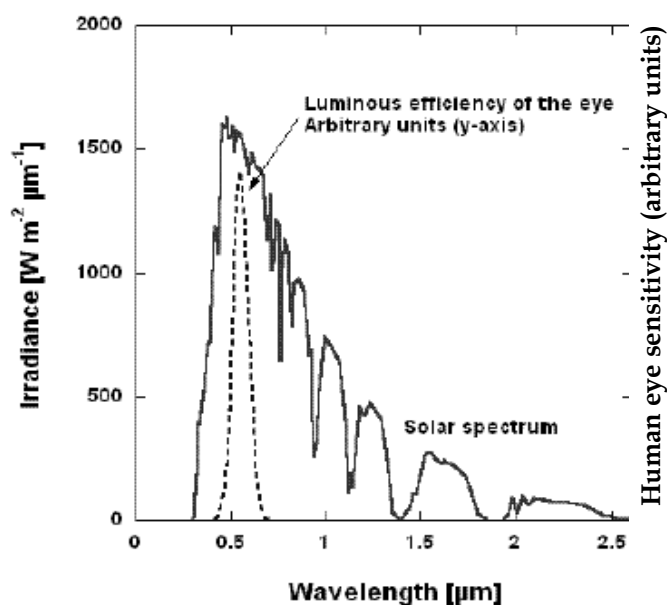


Fig. 1.1. Solar irradiation spectrum at air mass 1.5 and the relative spectral sensitivity of the human eye (ISO 9845-1, 1992)

## 1.2 Overview of photovoltaic technologies and materials

Research on solar cells can be divided into three areas: technologies that can make current solar cells cheaper and/or more efficient to effectively compete with other energy sources, developing new technologies based on new solar cell architectural designs and developing new materials to serve as light absorbers and charge carriers. The technologies can be classified into three generations.

The first generation photovoltaic cell consists of a large-area, single-crystal, single layer p-n junction diode, capable of generating usable electrical energy from light sources with the wavelengths of sunlight. These cells are typically made using a diffusion process with silicon wafers. First-generation photovoltaic cells are the dominant technology in the commercial production of solar cells, accounting for more than 86% of the terrestrial solar cels (Goetzberger and Hebling, 2000).

The second generation of photovoltaic materials is based on the use of thin epitaxial deposits of semiconductors on lattice-matched wafers. There are two classes of epitaxial photovoltaics - space and terrestrial. Space cells typically have higher air mass zero efficiencies in production, but have a higher cost per watt (Yamaguchi et. al, 2006, Takamoto et. al, 2006). There are a number of technologies/ semiconductor materials under investigation or in mass production. Examples include amorphous silicon, polycrystalline silicon, micro-crystalline silicon, cadmium telluride, copper indium diselenide/sulfide. An advantage of thin-film technology theoretically results in reduced mass so it allows fitting panels on light or flexible materials (Shah , et al. 2004). Thin GaAs-based films for space applications with very high potential air mass zero efficiencies are being produced (Merrill and Senft, 2007).

Third-generation photovoltaics are very different from the previous semiconductor devices as they do not rely on a traditional p-n junction to separate photogenerated charge carriers. For space applications, quantum well devices and devices incorporating carbon nanotubes are being studied with a potential for very high efficiency (Hoffmann, 2006). For terrestrial applications, these new devices include photoelectrochemical (Fahrenbruch and Bube, 1983) cells and polymer solar cells (Brabec et. al., 2001), among others.

## 1.3 The pn junction solar cell

The conventional p-n junction solar cell has a single energy band gap, $E_g$, so when the cell is exposed to solar radiation; a photon energy of less than $E_g$ makes no contribution to the cell output if phonon assisted absorption is neglected. A photon with energy greater than Eg contributes to energy $E_g$ to the cell output and the excess over $E_g$ is wasted as heat.

The equivalent circuit in Figure 1.2 shows a constant current source in parallel with the junction.

The source $I_L$ results from the excitation of excess carriers by the solar radiation. $I_s$ is the diode saturation current as derived by the Shockley equation (Sze, 1991) and $R_L$ the load resistance. The shunt resistance $R_{sh}$ is caused by surface leakage along the edges of the cell, and by metal shorts in defects and grain boundaries. The series resistance is as a result of the front and back contact resistance, the base resistance and the thin top layer resistance. Ideally $R_s = 0$ and $R_{sh} = \infty$ , but even for a high value of $R_{sh}$ (say about 100 $\Omega$) its effect on the *I-V* characteristics of the cell is negligible. So it is $R_s$ that should be kept as low as possible.
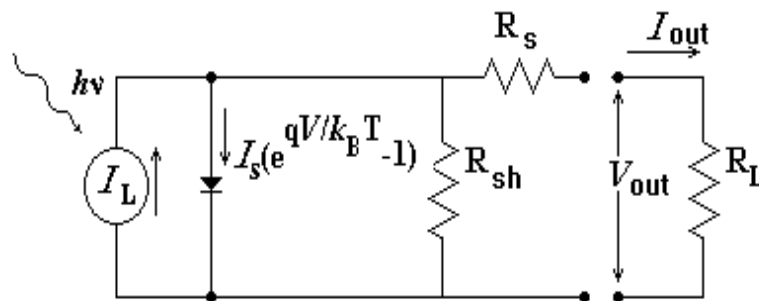
Fig. 1.2. Equivalent circuit of a solar cell

The *I-V* characteristics of such a device are given by

$$I = I_s(e^{qV/k_BT} - 1) - I_L ,$$ (1.3)

One important parameter of the cell, open circuit voltage $V_{oc}$ is related to the $I_L$ and $I_s$ as

$$V_{oc} = \frac{k_BT}{q}\ln\left(\frac{I_L}{I_s} + 1\right) \approx \frac{k_BT}{q}\ln\left(\frac{I_L}{I_s}\right)$$ (1.4)

and since *I* = 0, hence for a given $I_L$, the open circuit voltage increases logarithmically with decreasing saturation current $I_s$.

### 1.3.1 Loss mechanisms in pn junction solar cell

#### 1.3.1.1 Surface reflection losses

On the top of the solar cell, reflection of incident solar energy do occur and affect short circuit current of the cell. This is because refection reduces the absorbed carriers and hence the $I_{sc}$. For a bare silicon, these losses account for more than 30% due to high reflectivity of silicon in the UV and visible regions which is about 0.3 (Green, 1992), However use of antireflective coatings and texturing of the surface are some of the methods used to minimize efficiency loss by top surface reflection.

#### 1.3.1.2 Recombination losses

Basically, photovoltaic conversion occurs through three separate processes: (1) the absorption of light to create electron-hole pairs in an appropriate semiconductor; (2) collection and separation of these carriers by an internal electric field; (3) distribution to an external load. Photon incident on the solar cell generates electron hole pairs; Generated carriers need to be separated before they recombine, with emission of energy. Recombination causes loss of carrier and reduces the open circuit voltage $V_{oc}$ of the cell.

Recombination can occur by having an electron from the conduction band combining with the hole in the valence band with emission of energy, the so called band-to-band recombination. Another recombination method which is the dominant form in solar cells is trap assisted type. This is attributed to impurities present in the semiconductor which introduce an additional energy level within the forbidden energy gap. This added energy level acts as a trap and captures electrons and holes leading to recombination.

Also, the surface of the solar cells have large number of dangling bonds due to abrupt termination of crystal structure. These dangling bonds act as recombination centers. Carriers generated at the surface fall in to the dangling bond and recombine with the hole.

Another type of recombination referred to as Auger recombination occurs when a solar cell is exposed to high intensity of photons. It may involve two electrons and a hole or two holes and an electron. When hole from the valence band recombine with the electron in the conduction band the excess energy released during recombination is absorbed by the neighboring electron in the conduction band which then goes to some higher energy level and then again falls back to the conduction band with release of energy.

### 1.3.1.3 Series resistance losses

As already explained in the previous section, series resistance losses arises from power loss due to $R_s$. and contribute to around less than 20% of the total input power (Markvart, 1994). The losses increase tremendously when solar cell is operated at high intensities and they are the subject of this chapter.

## 1.4 Concentrating photovoltaics

Concentrating Photovoltaic systems use a large area of lenses or mirrors to focus sunlight on a small area of photovoltaic cells. Concentration of sunlight onto photovoltaic cells, and the consequent replacement of expensive photovoltaic area with less expensive concentrating mirrors or lenses, is seen as one method to lower the cost of solar electricity. Because of the reduction in solar absorber area, more costly, but higher efficiency PV cells may be used (Dalal and Moore, 1997; Kurtz and Lewandowski, 2004).

### 1.4.1 Concentrator geometries

### 1.4.1.1 Single cells

In small point-focus concentrators, sunlight is usually focused onto each cell individually. This means that each cell has an area roughly equal to that of the concentrator available for heat sinking, as shown in Fig. 1.3. Single cell systems commonly use various types of lenses for concentration (Royne et. al., 2005).
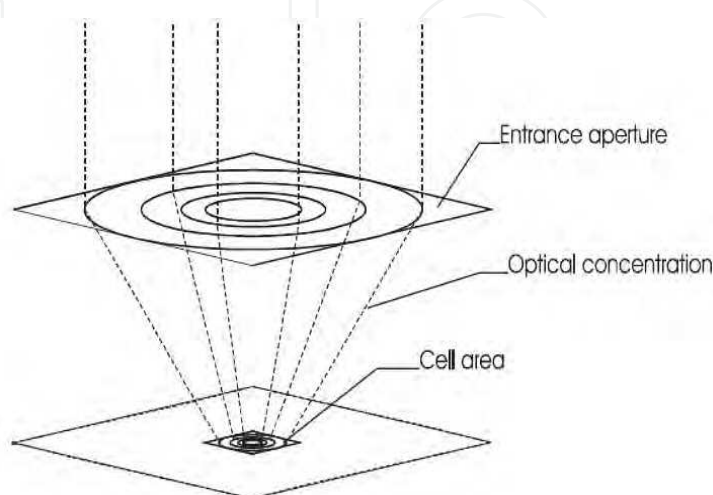


Fig. 1.3. Single-cell concentrator (Royne et. al., 2005)

### 1.4.1.2 Linear geometry

Line focus systems typically use parabolic troughs or linear Fresnel lenses to focus the light onto a row of cells as shown in Figure 1.4. The areas available for heat sinking extend from two of the sides and the back of the cell. Compound parabolic concentrators (CPC) shown in Figure 1.5 fall under this category and have been used for PV and thermal applications and have been well discussed in literature (Winston, 1974; Tabor, 1984; Brogren et. al.,  2000) .
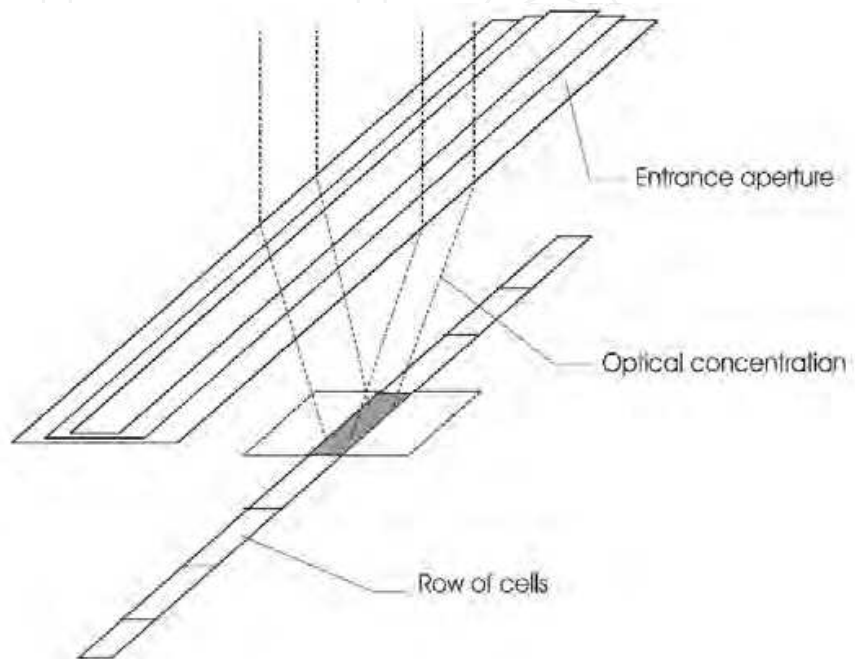


Fig. 1.4. Linear concentrator (Royne et. al., 2005)



Fig. 1.5. Photograph showing an array of compound parabolic concentrators for PV and Thermal application

### 1.4.1.3 Densely packed modules

In larger point-focus systems, such as dishes or heliostat fields, the receiver generally consists of a multitude of densely packed cells as shown in Figure 1.6. The receiver is usually placed slightly away from the focal plane to increase the uniformity of illumination. Secondary concentrators may be used to further improve flux homogeneity (Kreske, 2002).
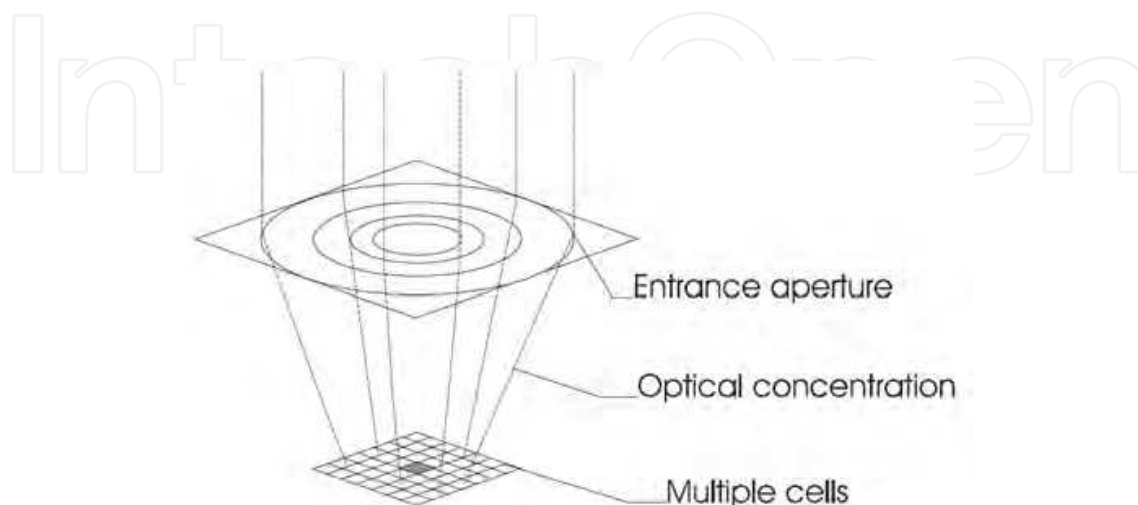


Fig. 1.6. Densely packed cells (Kreske , 2002)

## 1.5 Design considerations

Only a fraction of the incoming sunlight striking a solar cell is converted into electrical energy. A typical efficiency value for concentrator cells is about 25% (Royne et. al, 2005). The remainder of the absorbed energy is converted into thermal energy in the cell and may cause the junction temperature to rise unless the heat is efficiently dissipated to the environment. The major design considerations for cooling of photovoltaic cells are given below:

### 1.5.1 Cell temperature

The four main parameters used to characterize solar cell outputs are the short circuit current, $I_{sc}$, the open circuit voltage, $V_{oc}$, the fill factor, FF, and the conversion efficiency, $\eta_x$. In order to evaluate the conversion efficiency of systems where the radiation is concentrated it is important to calculate the influence of the value of the solar flux on the efficiency. The ratio of the illumination level incident on a cell to the level corresponding to AM1.5 illumination is the concentration factor. At constant temperature the short circuit current is proportional to the concentration factor (Green, 1992). An influence on the efficiency results from the relation between $V_{oc}$ or FF and illumination level. The fill factor is strongly dependent on the series resistance, $R_s$, of the solar cell. This has profound consequences on the efficiency of a cell working under concentrated sunlight because the power loss, caused by $R_s$, increases with the square of the current. For a silicon solar cell with conversion efficiency of about 24% at 293 K, its efficiency reduces to less than 10% if the temperature goes beyond 400 K (Figure 1.7).
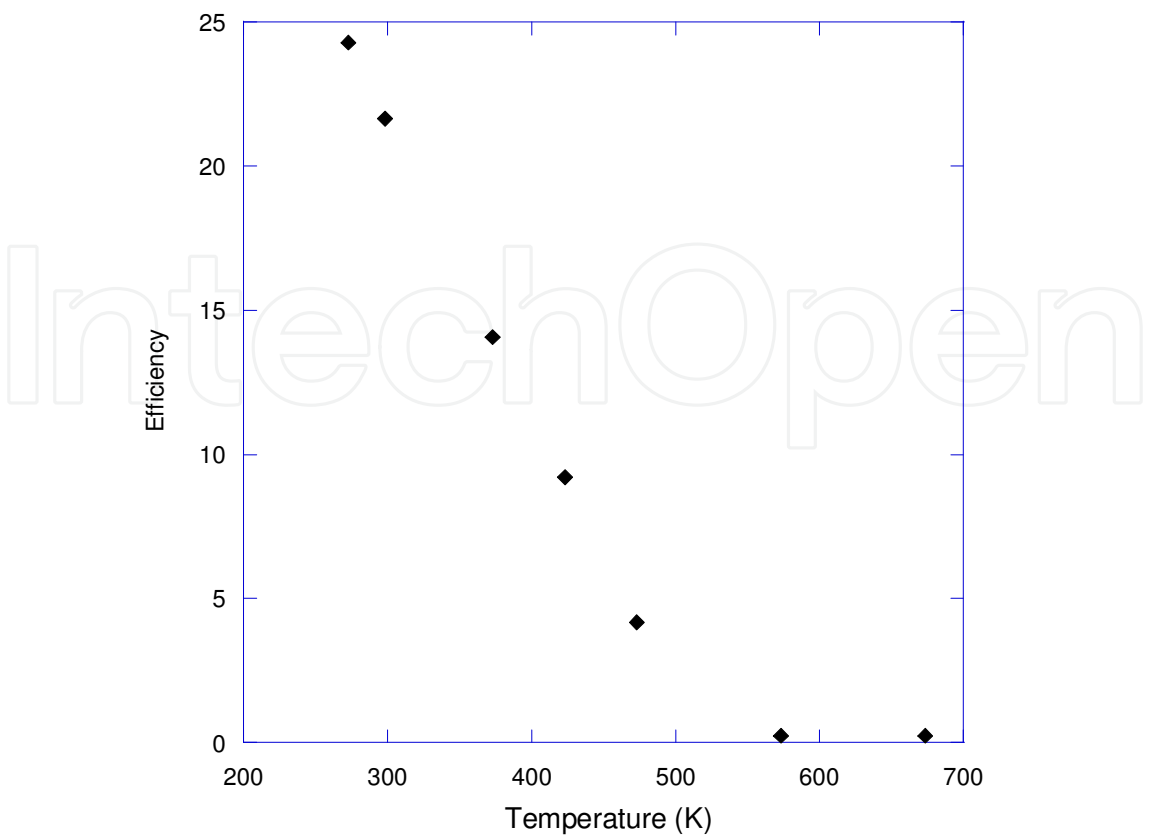
Fig. 1.7. Theoretical silicon solar cell efficiency as a function of temperature. The data was extracted from Fig. 7 in Wysocki and Rappaport, 1960 using digitization software.

### 1.5.2 Uniformity of temperature

The cell efficiency is known to decrease due to non-uniform temperatures across the cell (Luque et. al, 1998; Mathur et. al, 1984; Chenlo, 1987). In a photovoltaic module, a number of cells are electrically connected in series, and several of these series connections can be connected in parallel. Series connections increase the output voltage and decrease the current at a given power output, thereby reducing the ohmic losses. However, when cells are connected in series, the cell that gives the smallest output will limit the current. This is known as the 'current matching problem'. Because the cell efficiency decreases with increasing temperature, the cell at the highest temperature will limit the efficiency of the whole string. This problem can be avoided through the use of bypass diodes (Edenburn and Burns, 1981) which bypass cells when they reach a certain temperature or by keeping a uniform temperature across each series connection. Also, the cells exhibit long-term degradation if the temperature exceeds a certain limit (SunPower, 2002; Horne, 1993). The cell manufacturer will generally specify a given temperature degradation coefficient and a maximum operating temperature for the cell.

### 1.6 Cooling options for solar cells

As already indicated in the previous sections, the energy conversion efficiency of solar cells decreases as the temperature of the solar cells increases. Furthermore, increasing temperature may also have detrimental effects on other components of the photovoltaic

system, including thermal stress which may result in failures in the photovoltaic system. Whether the cells are singular, linear or densely packed, passive or active cooling can be employed to maintain low operating temperatures depending on the complexity and the scale of the concentrating PV system.

To keep operational costs to a minimum, a simple and low maintenance solution should be sought. This also includes minimizing the use of toxic materials due to health and environmental concerns. Reliability is another important aspect because a failure of the cooling system could lead to the destruction of the PV cells.

A passive convection cooling system for photovoltaic panels utilizes principles of aerodynamics to channel natural air flow across photovoltaic panels to increase the rate of heat transfer and increase the convection rate and decrease the temperature of the photovoltaic panels thereby increasing the efficiency of the solar cells and increasing the durability of the photovoltaic system. There is a wide variety of passive cooling options available. The simplest ones involve solids of high thermal conductivity, like aluminium or copper, and an array of fins or other extruded surfaces to suit the application. More complex systems involve phase changes and various methods for natural circulation.

Active cooling systems are a little bit more complicated. They require additional hardware and costs such as a heat pump device having a refrigerating cycle comprising a compressor, a heat radiator, a decompression device, a heat exchanger etc. The advantage of such a system is the possibility of cogeneration – electrical and thermal energy.

## 1.7 Spectrally selective solar reflectors SSR

In principle, any transparent conductor film deposited on a reflecting surface exhibits to some degree of spectral selectivity. Aluminium is commonly used as a reflecting material basically due to its very high specula reflectance and its relatively low cost. Parabolic or planar aluminium reflectors are common in concentrating troughs for photovoltaics, but they are not spectrally selective. This leads to the concentration of light that is not useful in the production of electricity in the PV cells and is dissipated in the system as heat

A possible way of reducing the heat buildup on a solar cell is to have only the photons with energy greater than the band gap of the absorber to illuminate the cell. Thus, if the reflecting concentrator is replaced with a spectrally selective reflector (SSR), the SSR should separate the radiation necessary for electricity production from the solar radiation and be directed to the cell (Figure 1.8).

In some materials like transparent conductors, the spectral position of the plasma absorption band can be tailored with doping and can reflect selectively when coated on a reflecting surface by absorbing radiation in the near infra red region with the relationship between plasma frequency $\varpi_P$ and carrier concentration $n_e$ being

$$\omega_P^2 = \frac{n_e q^2}{\varepsilon_0 m_e}. \tag{1.5}$$

where, $m_e$ and $q$ are the electron mass and electron charge respectively while $\varepsilon_0$ is the permittivity of free space.

Some good examples are doped tin oxide, zinc oxide and indium tin oxide. Due to the hardness and inertness of some oxides, they also serve as an excellent protective layer to the aluminum surface.

The ideal properties of an SSR for use with crystalline silicon solar cells are shown in Fig. 1.9. The wavelength $\lambda_c$ for switching from high to low reflectance lies at 1100 nm and corresponds to the silicon band gap. $R_{cell}$ and $R_{therm}$ are the integrated reflectance values which for a Si solar cell are given by

$$R_{cell} = \frac{\int_{300}^{1100} G(\lambda)R(\lambda)d\lambda}{\int_{300}^{1100} G(\lambda)d\lambda} \quad , \tag{1.6}$$

$$R_{therm} = \frac{\int_{1100}^{2500} G(\lambda)R(\lambda)d\lambda}{\int_{1100}^{2500} G(\lambda)d\lambda} \quad , \tag{1.7}$$

where $G(\lambda)$ is the AM 1.5 solar spectrum [19]. For an SSR with ideal properties, $R_{cell} = 1$ and $R_{therm} = 0$ will ensure that solar radiation in the range $300 < \lambda < 1100$ nm is reflected towards the solar cell while the rest is absorbed by the SSR and hence does not contribute to the heating of the solar cell.
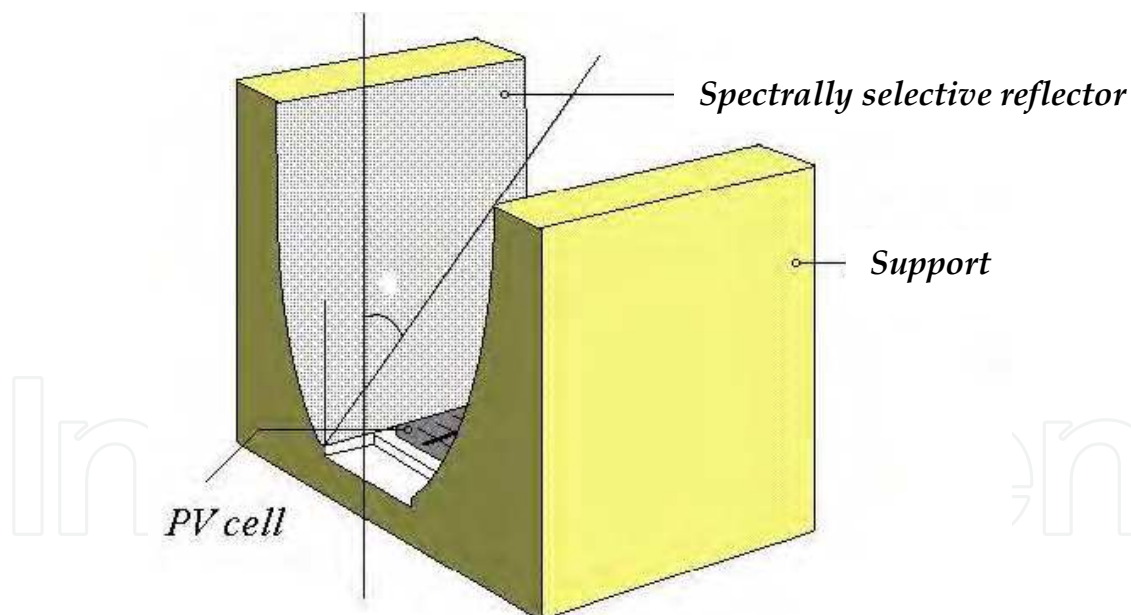


Fig. 1.8. Integration of a spectrally selective reflector surface on a PV concentrator

### 1.7.1 The SSR model

The basic optical properties of a transparent conductor (TC) coated aluminum reflector are hypothesized. Here energy absorption from plasma oscillations in degenerate transparent-conducting-oxide semiconductor films in combination with a highly reflecting metal substrate can be used in the fabrication of solar selective reflector surfaces (Figure 1.10).

The classical Drude theory for metals is often used to calculate the optical constants $n$ and $k$ for the TCs and Fresnel's formulae is employed for the reflectance simulations.
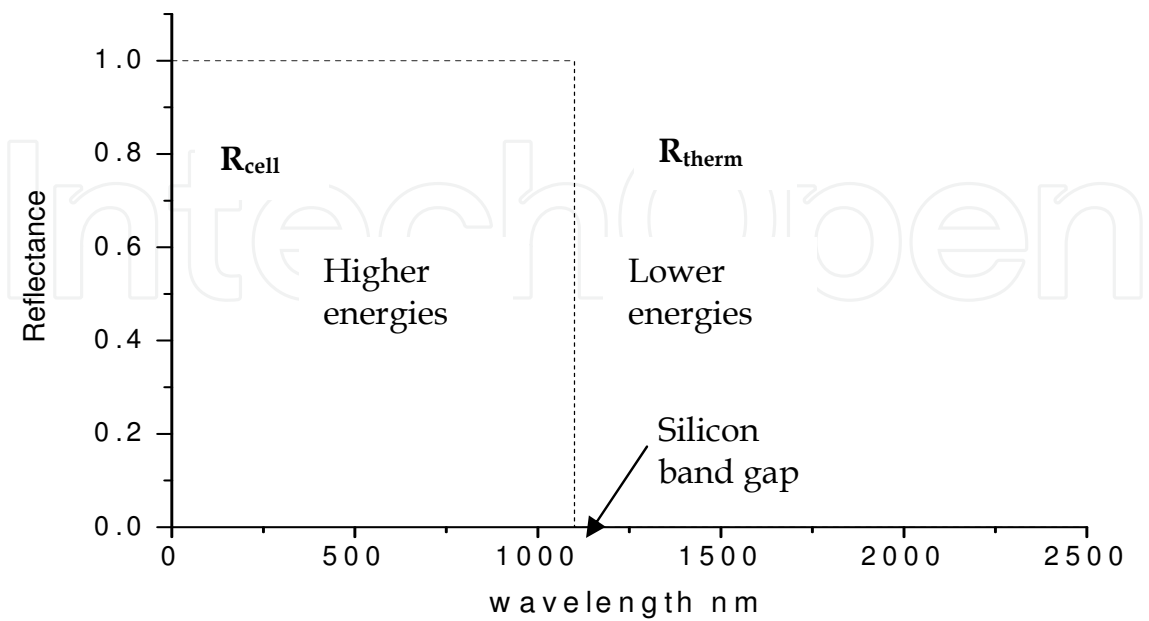


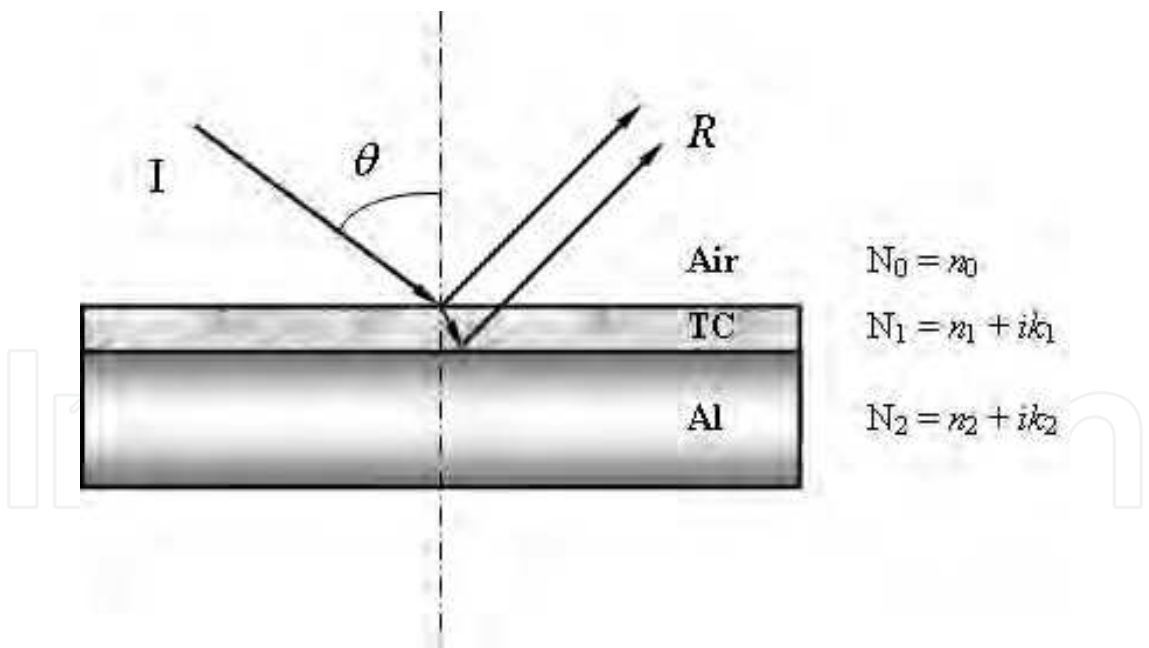Fig. 1.9. Ideal Reflectance properties of an SSR



Fig. 1.10. Theoretical model used for the reflectance simulations.

The Drude model gives a phenomenological approach to the problem, based on some of the fundamental material properties of TCs as the DC mobility, the effective mass and the concentration of the free charge carriers. As the plasma absorption shifts to shorter wavelengths for higher doping concentration, an optimum doping can be found theoretically for a specific choice of SSR.

So far two types of SSR surfaces have been studied - one based on fluorine doped tin oxide and the other on niobium doped titanium oxide. For both cases a thin layer of aluminium oxide was sandwiched between the oxide conducting oxide and aluminium. Figure 1.11 shows the optical properties of $TiO_2:Nb/Al_2O_3/Al$ SSR surfaces deposited by DC Magnetron sputtering tailored for Si solar cell application with minimum reflectance centred around 1500 nm.
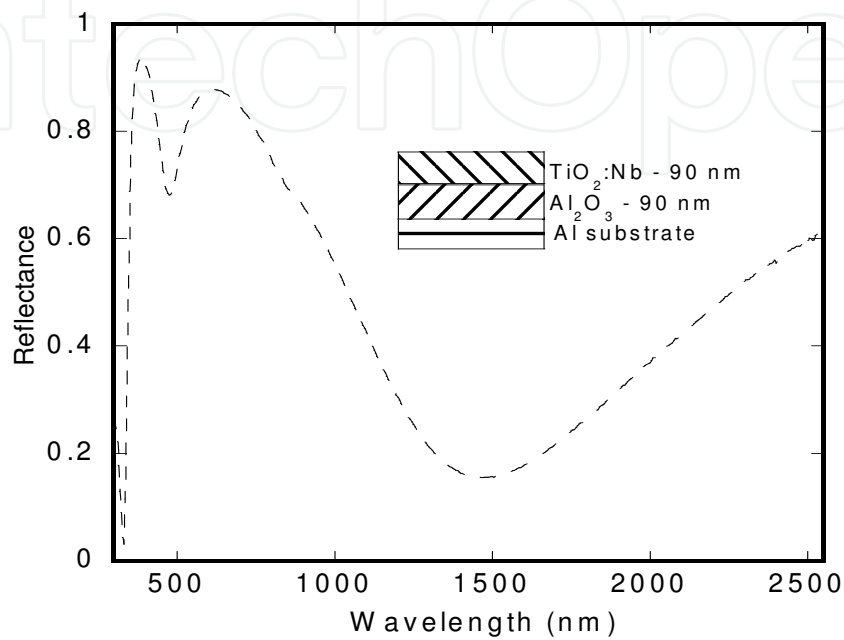


Fig. 1.11. Experimental spectral reflectance for a $TiO_2:Nb/Al_2O_3/Al$ structures. The layer thicknesses are indicated.
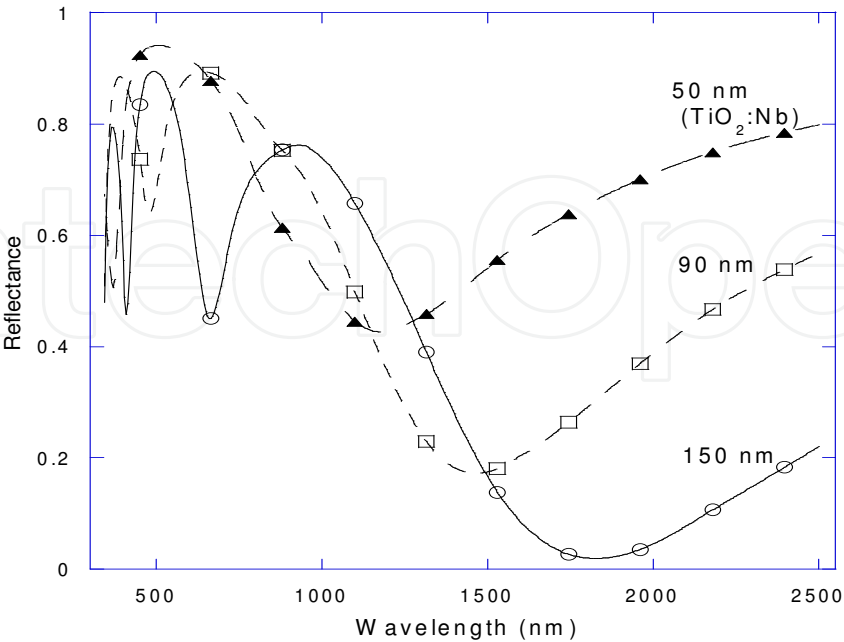


Fig. 1.12. Influence of the thickness of $TiO_2:Nb$ film on the reflectance of the SSR. $Al_2O_3$ thickness is 90 nm (Maghanga et al, 2011).

Expectedly, the properties of SSR such as those plotted in Figure 1.11 vary with thickness of the layers as shown in Figure 1.12 and 1.13. An optimum must therefore be established which can be achieved by mathematical modelling of the multilayer structure. This requires the knowledge of optical data of the substrate, TCO and the intermediate layer (Maghanga et. al, 2009).
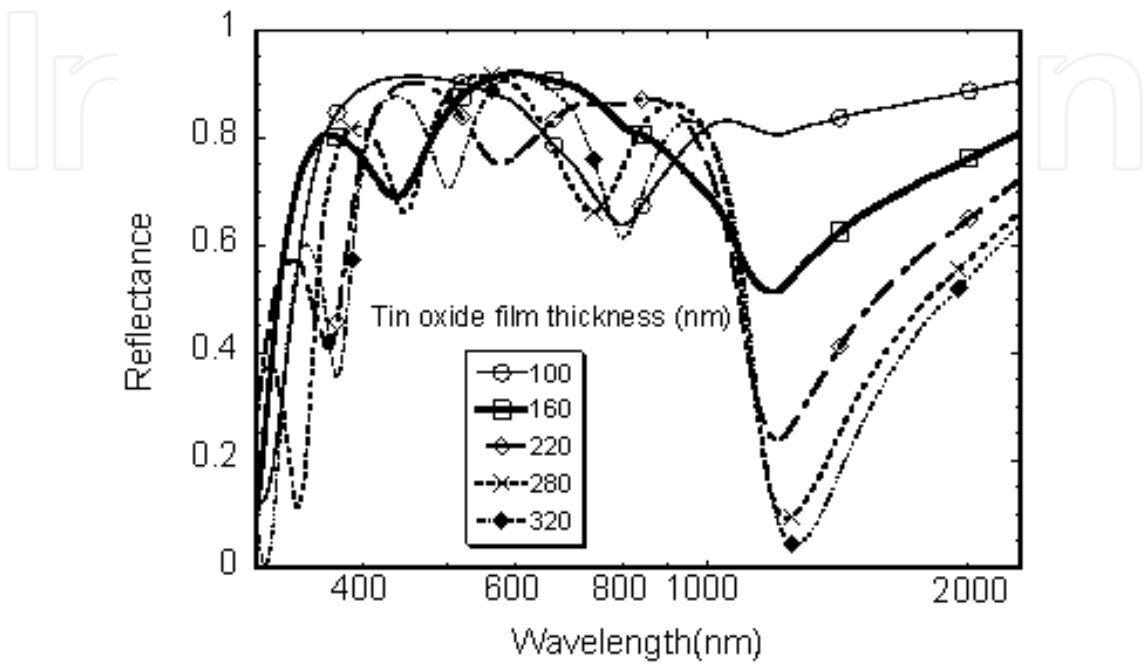


Fig. 1.13. Computed reflectance spectrum for 100, 160, 220, 280 and 320 nm thick fluorine doped tin oxide on aluminum (Mwamburi et al., 2000)

### 1.7.2 Heat balance on solar cell

The energy conservation equation for concentrator solar cells is crucial is estimating the temperature of the solar cell when concentration varies which for concentrator cells employing parabolic concentrators and can be expressed as

$$\xi \alpha A_o C q_o - \eta \xi \alpha A_o C q_o - A_r \varepsilon \sigma_B (T^4 - T_o^4) - A_c h (T - T_o) = 0 , \qquad (1.8)$$

where the first term denotes the luminous power reflected to the cell with reflectance $\xi$, the cell surface absorptivity $\alpha$, the cell area $A_o$, the geometric concentration ratio C and the energy density $q_o$. The second term in the equation is the electric power delivered to the external load with the conversion efficiency $\eta$. The third term represents the power dissipated through radiation with the surface area $A_r$, the surface emissivity $\varepsilon$, the Stefan-Boltzmann constant $\sigma_B$, the surface temperature $T$ and the ambient temperature $T_o$. The last term characterizes the power dissipated through convection, which depends on the surface area $A_c$ and the convective transfer coefficient h.

If a cell relies only on the cell surface area for cooling through radiation and convention, equation 1.8 reduces to

$$\xi\alpha Cq_o - \eta\xi\alpha Cq_o - \varepsilon\sigma_B(T^4 - T_o^4) - h(T - T_o) = 0 \tag{1.9}$$

For case of a concentrator cell employing a reflector material with SSR properties, the cell absorbs only the useful radiation i.e., energy corresponding to the wavelengths $\leq \lambda_C$ while without the SSR property the wavelength range of absorption spans the whole solar spectrum, say $300 \leq \lambda_C \leq 2550nm$. Using the parameters in Table 1, the variation of temperature with concentration for a solar cell with and without an SSR was estimated using equation 1.8 and plotted in Figure 1.14. At low concentration ratios, the cell temperature is low and the difference in temperature between the two cases is small. The effect of the SSR is evident at higher concentration ratios where the temperature of the cell without the SSR is higher than that with the SSR. The model assumes minimum cooling from convection and radiation such that $A_r = 4A_0$ and $A_c = 10A_0$.

| Parameter | Description | Value |
|---|---|---|
| $\alpha$ | Surface absorptivity of the cell | 0.85 |
| $\eta$ | Efficiency of the cell | 0.2 |
| $\tau_0$ | Ambient temperature | 300 K |
| $H$ | Convective heat transfer | 5 W/m²K |
| $C$ | Concentration factor | Variable |
| $\varepsilon$ | Emissivity of the cell | 0.85 |

Table 1. Parameters used in calculations of solar cell temperature (Maghanga et. al, 2011)
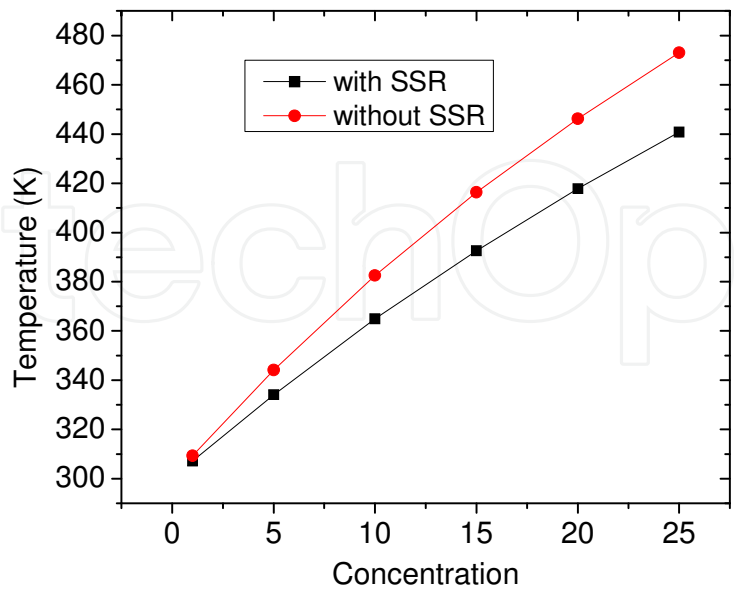


Fig. 1.14. Solar cell temperature *versus* concentration calculated for constructions with and without a SSR. The following values were assumed: $A_r = 4A_0$ and $A_c = 10A_0$ (Maghanga et. al, 2011).

### 1.7.3 Evaluation of SSR

The extent at which the SSR reflects solar in the region below and above the solar cell band gap $E_g$ can be calculated for silicon solar using equation 1.6 and 1.7. For instance, for the SSR properties shown in Figure 1.11, the $R_{cell}$ and $R_{thermal}$ values are 0.756 and 0.28 respectively. Based on this data, a Figure of Merit (*FOM*) of an SSR can be estimated using the formula (Maghanga et. al, 2011):

$$FOM \approx 0.8 + 0.2 \frac{R_{therm}}{R_{cell}}. \tag{1.10}$$

The value attains a minimum value of 0.8 for an ideal SSR and should approach this value as closely as possible for real SSR coatings. For a non-selective reflecting surface, the *FOM* is equal to 1.0.

## 2. Conclusion

This chapter has explained various loss mechanisms in a pn junction solar cell with emphasis on losses due to heat build-up on concentrator cells. Using the heat balance equation, the chapter has illustrated the possible contribution of the SSR to heat reduction on a solar cell. Specific experimental cases have been cited including a formula that can be used to evaluate the quality of a spectrally selective reflector surface.

## 3. Acknowledgements

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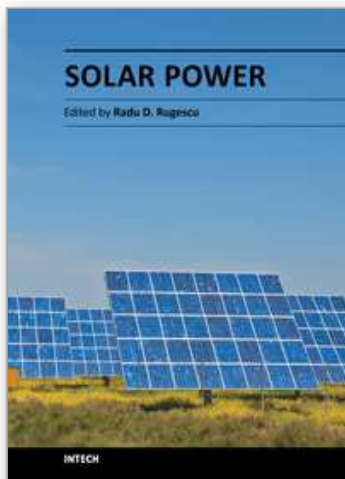
**Solar Power**

Edited by Prof. Radu Rugescu

A wide variety of detail regarding genuine and proprietary research from distinguished authors is presented, ranging from new means of evaluation of the local solar irradiance to the manufacturing technology of photovoltaic cells. Also included is the topic of biotechnology based on solar energy and electricity generation onboard space vehicles in an optimised manner with possible transfer to the Earth. The graphical material supports the presentation, transforming the reading into a pleasant and instructive labor for any interested specialist or student.

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