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THEORETICAL PERFORMANCE OF TWO ULTRA-HIGH EFFICIENCY PHOTOVOLTAIC CONCEPTS

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ABSTRACT

Two photovoltaic energy conversion concepts capable of producing electricity at substantially higher efficiencies than conventional PV systems are the thermo-photovoltaic (TPV) concept and the tandem-cell (TC) concept. The theoretical performance of devices designed to manifest these concepts is investigated in this paper. It appears that significant efficiency increases are possible with these two concepts if one is prepared to accept the inherent added complexity. For example, in the TPV device, for a maximum allowable diffuser temperature of 2500 deg K, a theoretical efficiency of 65% is predicted. Theoretical efficiencies near 50% are predicted for the TC device.

1. ENERGY IRRADIATION

The energy irradiation of unconcentrated and undiluted solar radiation upon a photovoltaic (PV) convertor in the earth's orbit and oriented normal to the sun's rays is given by

$$G_c = F_{cs}\,\sigma\,T_s^4 \qquad (1)$$

where F_{CS} is the convertor-to-sun view factor, $(R_S / R_{eO})^2$, where R_S is the radius of the sun and R_{eO} is the radius of the earth's orbit ($F_{CS} = 2.161 \times 10^{-5}$), σ is the Stefan-Boltzmann constant (5.67×10 W/m K^4) and T_S is the temperature of the sun (considered a blackbody at 5770 K). G_C works out to be 1358 W/m. Only a fraction of this irradiation can be converted into work.

2. EFFICIENCY OF A PV DEVICE

In their famous 1961 paper [1], Shockley and Queisser defined an "ultimate" efficiency for any device employing a photovoltaic process in which: (1) photons with energy less than E_g (the gap energy) produce no effect, and (2) each photon with energy greater than E_g produces an electronic charge at the terminals at a voltage equal to E_g.

They assumed further that the PV device is subject to blackbody radiation from the sun. They found a maximum efficiency of 44% at an optimum gap energy of 1.1 eV, corresponding closely to silicon. This efficiency is an overestimate since: (1) not all the electron-hole pairs generated by absorbed photons arrive at the terminals and those that do are at a voltage less than the gap energy, and (2) the capture coefficient is not a step-function of energy (zero below the gap energy and unity above).

If we retain only the step-function capture coefficient assumption, the generated current density is given by

$$I_g = q\,\pi\,F_{cs}\int_{u_o}^{\infty} K_u\,du \qquad (2)$$

where q is the electronic charge, K_u is the spectral photon intensity of solar radiation, u is the photon energy, and u_O is the gap energy (E_g). K_u is given by

$$K_u = \frac{2\,\nu^2}{h\,c^2\left(e^{z_s} - 1\right)} \qquad (3)$$

where z_S is a dimensionless energy given by

$$z_s = \frac{u}{k\,T_s} \qquad (4)$$

In these equations h is Planck's constant, u is frequency, c the speed of light and k Boltzmann's constant. In terms of dimensionless energy the generated current density can be written

$$I_g = q\,F_{cs}\,\frac{15\,\sigma\,T_s^3}{k\,\pi^4}\int_{z_{so}}^{\infty}\frac{z_s^2}{e^{z_s} - 1}\,dz_s \qquad (5)$$

where z_{SO} is Eq. (4) evaluated for u_O. The actual current density is given by the familiar rectifier equation

$$I = I_g - I_s\left[e^{\frac{qV}{kT}} - 1\right] \qquad (6)$$

where V is the terminal voltage and the second term is the so called dark current density with I_g the saturation current density. A reasonable estimate of the minimum value of the saturation current density (amps/m^2) as a function of energy gap is [2]

$$I_s = 1.5 \times 10^9 e^{\frac{-E_g}{kT}} \qquad (7)$$

The cell voltage would be selected so as to maximize the power density where the power density is simply

$$P = I V \qquad (8)$$

The convertor efficiency is simply the ratio of the maximum power density determined in this way divided by the irradiation. Thus

$$\eta = \frac{P_{max.}}{G_c} \qquad (9)$$

Calculations reveal that in this case the maximum efficiency is about 26% at a gap energy of about 1.4 eV, corresponding this time closely to GaAs.

We will now look at two concepts for attaining higher efficiencies assuming the availability of convertors with any desired gap energy.

3. THE THERMOPHOTOVOLTAIC (TPV) CONCEPT

In the TPV energy convertor the solar radiation is concentrated before being directed to the cell, and a diffuser (assumed to be a blackbody) is interposed between the concentrator and the cell. Now, radiation from the sun, concentrated by a factor n by the concentrator, is intercepted and absorbed by the diffuser. The diffuser emits hemispherical radiation all of which strikes the cell. Since the transformation of beamed radiation into diffuse radiation lowers its temperature, the radiation now received by the cell is shifted spectrally toward the lower frequencies, hence lower energies. This spectral shift results in fewer photons with energies exceeding the gap energy striking the cell, but since photons with less than the gap energy are not absorbed by the cell, they can be reflected back to the diffuser by a reflector placed immediately behind the cell resulting in less energy loss. The net effect on the efficiency is not obvious. We will now determine these efficiencies as a function of concentration, n, and gap energy, E_g.

First of all we will determine the temperature of the diffuser. The irradiation on the diffuser is

$$G_d = n F_{ds} \sigma T_s^4 \qquad (10)$$

where F_{ds} is the same as F_{cs}. The radiation from the diffuser toward the cell (with a view factor of one) is

$$E_d = \pi \int_0^\infty H_u \, du \qquad (11)$$

where H_u is the spectral energy intensity given by u K_u. Of this

$$\pi \int_{u_g}^\infty H_u \, du$$

is absorbed by the cell and

$$\pi \int_0^{u_g} H_u \, du$$

passes through the cell and is reflected back to the diffuser. In terms of dimensionless energy, an energy balance on the diffuser can be written

$$n F_{ds} \sigma T_s^4 = \frac{15 \sigma T_d^4}{\pi^4} \int_{z_{dg}}^\infty \frac{z_d^3}{e^{z_d} - 1} \, dz_d \qquad (12)$$

where T_d is the diffuser temperature and

$$z_d = \frac{u}{k T_d} \qquad (13)$$

Eq. (12) is an equation for T_d as a function of n. The results are shown in Table 1 in terms of E_g and n

Table 1. Diffuser Temperature, T_d (deg K)

E_g	n				
	1	10	100	1000	10000
0.8	1039	1330	1803	2636	4192
1.0	1195	1502	1987	2816	4336
1.2	1345	1668	2168	3000	4497
1.4	1490	1830	2345	3185	4668
1.6	1632	1987	2519	3370	4845

We see from this table that the required diffuser temperature increases with both the gap energy and the concentration ratio. We will now proceed to calculate the maximum attainable power at these values of E_g and n.

The generated current density is given by

$$I_g = \frac{15\, q\, \sigma\, T_d^3}{k\, \pi^4} \int_{z_{do}}^{\infty} \frac{z_d^2}{e^{z_d} - 1}\, dz_d \qquad (14)$$

This I_g is substituted for the I_g given by Eq. (5) for the power output, which will depend on the terminal voltage, V. The terminal voltage which maximizes the power is found and the corresponding power per unit area of collected radiation (i.e., before concentration) is determined. The results of these calculations for the maximum power are shown in Table 2.

Table 2. Maximum Power Density, P_{max} (Watts/m^2)

E_g	n				
	1	10	100	1000	10000
0.8	521	579	614	608	540
1.0	645	689	713	703	636
1.2	735	767	785	773	712
1.4	804	827	839	827	769
1.6	860	874	883	869	815

The corresponding conversion efficiency is obtained by dividing these power densities by G_c (1358 W/m^2).

For example, if n is 100 and E_g is 1.4, the required diffuser temperature is 2345 deg K, the maximum power density is 839 W/m^2 corresponding to a theoretical conversion efficiency of 62%. The conclusions which can be drawn from these results are as follows:

1) The higher the gap energy the higher the diffuser temperature and power density.
2) There is an optimum concentration ratio of about 100 for all gap energies.

4. THE TANDEM CELLL CONCEPT

In this concept PV cells are stacked up one on top of the other in decreasing order of gap energies with the cell with the highest gap energy receiving the direct radiation from the sun. The radiation which is at too low an energy to be absorbed by the first cell passes through to the second cell which has a lower gap energy. The second cell absorbs a fraction of this energy and passes the remainder on to the third cell and so on. Each cell acts as an independent power producer with its own optimum voltage and maximum power. The current generated in the first cell is given by Eq. (5) with z_{so} corresponding to the gap energy of the first cell. The maximum power available from the cell is determined in the manner described in the text following Eq. (5). The current generated in the second cell is also given by Eq. (5) with the lower limit on the integral corresponding to the gap energy of the second cell and the upper limit corresponding to the gap energy of the first cell. Subsequent cells are treated in the same way and the total power output calculated as the sum of the power outputs of the individual cells.

Table 3 shows the results of such calculations for a tandem cell convertor with the individual gap energies as listed.

Table 3. Tandem-Cell Power Density, W/m^2

Cell No.	E_g	P_{max}	Total P_{max}
1	2.6	182.6	
2	2.2	104.4	
3	1.8	125.0	
4	1.4	126.5	
5	1.0	93.9	
6	0.6	26.5	658.9

The theoretical efficiency works out to be about 49%. We see from this table that the major contributors to the power output are the cells with gap energies near 1.6 eV. Adding more cells at the high gap-energy end increases the efficiency but at a decreasing rate (e.g., three more cells at gap energies of 3.0, 3.4, and 3.8 eV results in a theoretical efficiency only two points higher at 51%.

However, it must be noted that in this tandem-cell concept with each cell operating as an independent power producer the wiring would be very complicated for as many as six cells. Also, the need for materials with different gap energies means requiring very different processing technologies, the cost of which might be prohibitive. Therefore, tandem devices with only two or three cells or perhaps series-connected devices in which only two terminals are required might be preferable. Finally, it should be realized that since only blackbody radiation has been considered throughout this paper the efficiencies have been overestimated.

5. CONCLUSIONS

It appears, then, that significant efficiency increases are possible with these two concepts if one is prepared to accept the inherent added complexities. Concentration of the radiation in the tandem-cell concept would be beneficial but would appear to be an unjustified extra complexity.

6. REFERENCES

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Design and Process Innovations for High Efficiency Crystalline Solar Cells

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ABSTRACT

This paper discusses design features of high efficiency crystalline solar cells. The design requirements are established by consideration of minimizing optical and electronic losses in the cell. Some innovations in processing technologies, for fabrication of cells based on these designs, are also presented. Design issues of multijunction cells and up-to-date status of the performance of crystalline cells are also given.

Introduction:

During the past decade there have been many significant advances in all areas of photovoltaics (PV). On the commercial side, silicon and amorphous silicon modules are now available for a variety of terrestrial applications at a cost, typically $4 - 5 per Watt, that is competitive with other energy costs for such applications. In the laboratory, development of existing technologies and exploration of new materials have yielded significant improvements in efficiency with promise of better long term stability and lower production costs. Despite the relatively low level of federal research support, high efficiency technologies based upon crystalline semiconductors have kept pace with the advances in amorphous and polycrystalline approaches. As can be seen from Table I, many configurations of crystalline single junction cells, in silicon (Si) and III-V compounds, have reached efficiencies exceeding 20%. The multijunction cells, which use more than one material to provide better response over the broad spectrum, have attained performance levels consistent with theoretical predictions of providing about 50% better efficiency than the single junction cells, as seen from Table II.

This paper will focus on these high efficiency technologies in order to elucidate the optical and electronic design of solar cells and processing techniques necessary to make the above mentioned achievements possible.

Optical Design

The optical design of a solar cell involves incorporation of features that can effectively capture and transmit the incident broad-band optical flux into the solar cell and improve the flux distribution so as to create the most useful distribution of photogenerated carriers within the cell. Semiconductors like Si, GaAs and InP have high refractive indices, resulting in high reflection coefficient. Hence, it is important to minimize optical reflectance at the front surface of the cell. A conventional approach to accomplish this is to deposit an antireflection (AR) coating(s) on the front side of the cell. Design of such a coating is well known in optics where a single layer AR coating is used for producing a null in the reflectance at a given wavelength (λ). The relation between the film thickness (t), its refractive index (n) and the wavelength for zero reflectance is given by:

$$t = \lambda/4n \qquad \text{and } n = (n_1 * n_2)^{1/2}$$

where n_1 and n_2 are the refractive indices of the media above the cell and that of the cell, respectively. The materials used for such films include SiO_2, Si_3N_4, Ta_2O_5, ZnS and MgF_2. The reflectance of a single layer AR coated cell can be calculated according to formulas given in many text books on optics [1,2]. Fig.1 gives measured reflectance (air/cell interface) as a function of wavelength for a Si cell coated with a 900 Å layer of Si_3N_4, showing a null at 720 nm. It may be pointed out that if this cell is encapsulated, the reflectance at the encapsulant/cell interface would be changed, corresponding to the dotted line in Figure 1, which does not exhibit a null. In order to produce a null when encapsulated, the index of the coating should be 2.3. The dashed line shows the reflectance for such a film.

In a good optical design, it is not sufficient to merely minimize reflected power. The null location is, however, dictated by the following condition which relates to the internal spectral response, SR (λ), the input solar spectrum, $\phi(\lambda)$, and the cell transmittance [1 - R(λ)]:

$$\text{i.e} \quad \int SR(\lambda) * [1 - R(\lambda)] * \phi(\lambda)\, d\lambda$$

is maximum. This condition optimizes the short circuit current of the cell.

The null region of the reflectance can be significantly extended if the cell surface is rough or textured. This effect is seen from Figure 2 which shows the reflectance of a textured cell with an AR coating, consisting of 700Å thick Si_3N_4 on 100 Å of SiO_2 . For comparison, we have shown reflectance of polished Si wafer, coated with a similar film; also included are the reflectance characteristics of uncoated polished and uncoated textured silicon, illustrating the advantage of AR coating. In order to quantify the reflectance, these data may be weighted with respect to the input solar spectrum (AM1.5) to yield the average reflectance value of ~3% for AR coated textured silicon compared to ~10% for AR coated polished silicon [3].

An added advantage of texturing is that it converts normally incident light to oblique incidence within the cell. This feature leads to increased optical path length and light trapping; the latter is due to the fact that some of the scattered light is total internally reflected at the back-surface. For this reason texturing has been effectively employed for conventional Si solar cells and is becoming even more important to develop "thin" silicon solar cells (which offer advantage of reduced bulk recombination).

Until recently, texturing to increase the effective optical path length for GaAs, InP and other direct band-gap semiconductors was not deemed necessary because of their high intrinsic absorption (typical absorption depth ~2-3μm). In these cells a low reflectance broad-band effect is generally attained by means of a double layer AR coating, typically ZnS/MgF_2. Currently, there is considerable interest in studying light trapping in direct band-gap semiconductors for the following reason. Radiative recombination is the dominant mechanism in photo-generated carrier-loss for solar cells fabricated in high quality direct band gap semiconductors. Since the radiative recombination is accompanied by emission corresponding to the band-edge energy, it is possible to trap and reabsorb this light within the active region of the cell. Figure 3 shows schematically one approach of applying GaAlAs layers to reflect a portion of isotropically emitted light from reradiated photons in a thin film GaAs solar cell [4].

Another feature in optical design is minimization of the shadowing due to metal contacts. Typically a suitable grid design involves a compromise between the series resistance of the cell and the optical shadowing. Two approaches have been used to overcome this problem. In one case the contacts (and the junction) are located on the back-side of the cell leaving the entire front surface for photon impingement (Figure 4). This design requires that the front surface be well passivated and that the minority carrier diffusion length in the base region be very large [5]. The other approach is to employ a prismatic cover on the cell in a way that the cover deflects light above the metal grid into the open cell regions [6].

Electronic Design

The electronic design pertains to the most efficient collection of photo-generated carriers. In order to translate these into requirements for material/cell related electronic parameters it is necessary to consider the basic equation of the current for a cell operating at a voltage V, $I_{cell}(V)$, i.e

$$I_{cell}(V) = I_L - I_D(V)$$

where I_L and I_D represent the photo-generated and the dark currents, respectively. Expressions for I_L and I_D have been derived for many cell configurations; however, from qualitative considerations it is clear that optimum cell performance requires maximization of the photo-generated current and minimization of the dark current [7]. Fortunately, most of these demands can be met simultaneously by suitable choice of the material and cell parameters. For a given semiconductor the optimization of both photogeneration and dark current require: (1) low bulk recombination, (2) low carrier recombination at each interface, (3) reduced metal/semiconductor contact area. The demands on the dark current require, in addition, the choice of the cell parameters to minimize the injection component of the cell dark current. In the following we will briefly discuss how these parameter requirements can be met for high efficiency design.

Bulk recombination:

The short circuit current of a solar cell is strongly dependent on the minority carrier lifetime (τ) and related diffusion length (L). In turn, lifetime is dependent on the quality of the material determined by chemical purity and structural perfection. Clearly, to obtain highest efficiencies it is essential to start with substrates of high quality and to maintain the high lifetime throughout the cell fabrication. The highest efficiency silicon solar cells have been fabricated on Float Zone material of minority carrier lifetime ~10 m sec. The lower cost materials such as Czochralski (CZ), cast and ribbon materials have lower lifetime. In the case of CZ wafers the lifetime is primarily limited by impurities, whereas in the case of ribbons and cast wafers by both defects and