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Research

Limiting Photovoltaic Monochromatic Light Conversion Efficiency

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Notwithstanding the relatively low energy conversion efficiencies typical of standard solar photovoltaic systems, photovoltaic cells are shown, in principle, to be capable of converting well-collimated monochromatic light at efficiencies arbitrarily close to 100%. To approach such efficiencies, radiative recombination must be the main recombination process within the cell. The intensity of the monochromatic light must be high, and the cell should be designed so that it does not absorb or emit light outside the range of angles and wavelengths required to accept the incident monochromatic light. The thermodynamic basis of such high efficiency is also briefly discussed.

INTRODUCTION

The energy conversion efficiency of photovoltaic cells when converting solar radiation is limited to values below 33% for a standard single junction device,[1] largely owing to the wide bandwidth of the incident radiation. Carriers generated by high-energy photons quickly lose most of their excess energy above the band edge as they thermalise with the lattice. Experimentally, efficiencies of about 25% have been demonstrated for both silicon and GaAs devices.[2]

Conversion efficiencies for monochromatic light can be much higher since, by matching the photon energy and the semiconductor bandgap, the previous thermalisation loss can be avoided. Experimentally, conversion efficiencies of approximately 50% have been demonstrated for both silicon[3] and GaAs devices,[4] about double the value for broader bandwidth solar radiation. Such monochromatic light conversion is of interest for the powering of remote systems using energy beamed by laser, either across space[5] or along optical fibre communication systems. It is also of interest in thermophotovoltaic conversion when a source is used that emits narrow bandwidth radiation when heated, such as rare-earth-doped ceramics.[6]

The limiting efficiency of such a monochromatic converter is of interest to determine the scope for improvement in such applications. Earlier work has touched upon related issues when analysing the limiting performance of the two-level cell,[7] of the tandem cell[8] and of thermophotovoltaics.[9] The thermodynamics of monochromatic light conversion have also been recently discussed.[10] In the present work, it is shown that the limiting performance for monochromatic light is obtained for high-intensity light in cells designed to accommodate the spectral bandwidth and angular divergence of the incident light. In principle, conversion can occur with efficiency arbitrarily close to 100% when stimulated emission becomes appreciable within the cell.

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FORMULATION

Maximum photovoltaic efficiency occurs when all recombination in the cell is radiative. When an ideal cell is illuminated by a flux of photons, a particle balance is established between the electron flow between the cell terminals and the difference between the photon absorption and emission rates of the cell. If the cell is designed to collect all photogenerated carriers, it can be shown that electron and hole quasi-fermi level separation throughout the cell must be constant.[11] Such high collection efficiency can be ensured by assuming high carrier mobilities or by appropriate cell designs, such as by using a parallel multijunction structure.[12] Under such conditions, the above particle balance can be expressed as:[10,13]

$$J/q = \int_{E_G}^{\infty} \int_0^{2\pi} \int_0^{\pi/2} a \left[\dot{N} - \left(\frac{2}{h^3 c^2} \frac{E^2}{\{\exp[(E - qV)/kT] - 1\}} \right) \right] \cos\theta \, \sin\theta \, d\theta \, d\phi \, dE \tag{1}$$

where the cell absorbance a and the incident photon flux $\dot{N}$ are, in general, functions of photon energy E and angle of incidence on the cell, as defined in Figure 1(a), and qV is the ideal value of the quasi-Fermi energy separation. V is the applied voltage, T the cell temperature and other constants have their usual meaning.[10,13] For a given photon flux, a necessary condition for maximum efficiency is that the illuminating source has a narrow spectral width $\Delta\varepsilon$ and is well collimated, with all light incident within a solid angle $\Delta\Omega$. To ensure no incident photons are wasted, the cell absorbance should be unity over this range of energies and incident angles. However, finite absorbance outside this range reduces the energy conversion efficiency since this will increase the magnitude of the photon loss by light emission (second term on the right-hand side of Equation 1). Hence, the optimal cell will have zero absorbance outside this range so that Equation (1) with $\theta = 0$, reduces to:

$$J = q\dot{N} - \left(\frac{2q}{h^3 c^2} \right) \frac{E^2 \Delta\varepsilon \Delta\Omega}{\{\exp[(E - qV)/kT] - 1\}} \tag{2}$$

A conceptual approach to implementing such a cell is shown in Figure 1(b) where angularly and spectrally selective filters are used, either detached from the cell, integrated with the cell similarly to an anti-reflection coating, or as a combination of both.[14] (Alternatively, light concentrating schemes can provide matching

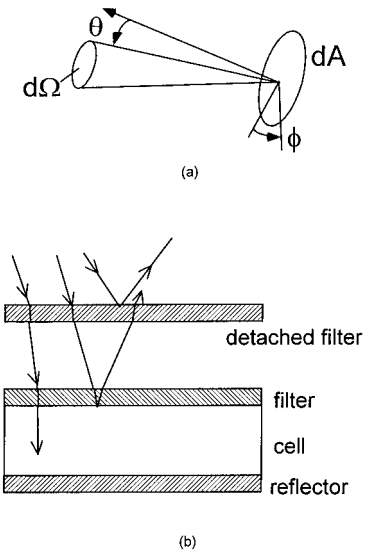

Figure 1. (a) Light within a cone of solid angle dΩ incident on an elemental surface area; (b) photovoltaic cell with detached and/or integrated filter providing spectral and angular selectivity

between the acceptance angle of the cell and the angular spread of the incident radiation.[14,15] The normalised output power p is found by multiplying by the output voltage V and dividing by the power in the incident photons ($\dot{N}E$):

$$p = [1 - kT\ln(y+1)/E][1 - 1/(yi)] \tag{3}$$

where

$$i = \left(\frac{h^3c^2}{2}\right)\frac{\dot{N}}{E^2\Delta\varepsilon\Delta\Omega} \tag{4}$$

i is the normalised light intensity and $y = \{\exp[(E - qV)/kT] - 1\}$ giving $V = E/q - (kT/q)\ln(y+1)$. The normalised power output will reach its peak at the maximum power point, found by differentiating with respect to the voltage-dependent parameter y. The condition for maximum power output becomes:

$$y(y - 1/i) - (y+1)[1 - kT\ln(y+1)/E]E/(kTi) = 0 \tag{5}$$

which can be solved iteratively, as for the standard solar cell case. As $\dot{N}$ and i increase, y decreases, allowing explicit solution for $y \ll 1$. This solution approaches the value $y = \sqrt{E/(kTi)}$ for large i, showing the maximum power point voltage approaches the value E/q arbitrarily closely as the photon flux increases. Highest efficiency can be obtained when i is large, i.e., for high photon fluxes, narrow bandwidth, well-collimated light, provided the cell is appropriately designed. In this case, the efficiency approaches a limiting value:

$$\eta = [1 - \sqrt{kT/(Ei)}]^2 \tag{6}$$

which can be arbitrarily close to unity at sufficiently high illumination levels.

RESULTS AND DISCUSSION

Figure 2 shows the variation of the normalised current–voltage relationship as the value of normalised intensity i increases. For small i or low illumination intensities, normal solar cell characteristics are apparent. As the intensity of the monochromatic light source increases, the curves 'square-up' as stimulated emission increases

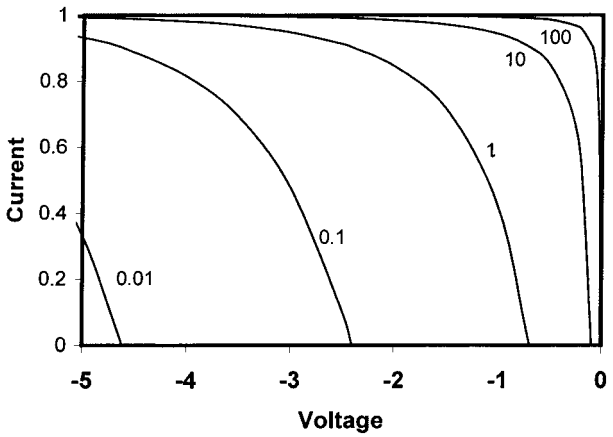

Figure 2. Calculated normalised current–voltage curves for an idealised solar cell for increasing normalised monochromatic light intensity, i. The voltage is expressed in units of kT/q below E/q, the potential corresponding to the photon energy, E

at the higher voltages. In thin devices, this tendency would be influenced by a decreasing absorbance as stimulated emission became significant with increasing voltage.[16,17] However, since the net absorption is always positive for positive y, absorbance values arbitrarily close to unity could be maintained, in principle, by sufficient device thickness.

Interestingly, provided the cell has the required selective absorbance, the same efficiency is obtained, in principle, regardless of any energy in excess of the semiconductor bandgap the incident photons may possess. All semiconductors would give a voltage output approaching that of the incident photon energy/q at high intensities, even if photon energy was higher than the cell bandgap. However, since the absorbance for photons of energy below the bandgap is ideally zero, the bandgap provides a convenient low energy filter if bandgap and photon energy are well matched. The use of the bandgap in this way might be expected to simplify the overall design of the selective filter as well as greatly reducing losses that might be expected in any practical, as opposed to conceptual, filter.

If the bandgap is used as the low-energy cut-off and no high energy cut-off filtering is used, similar performance to the idealised case can be obtained. The full integral of Equation (1) must be used in this case. The final result takes the form of Equation (2) but with the energy averaged value of $\Delta\varepsilon$ equal to kT applied, if unit absorbance is assumed for photon energies above the bandgap. If absorbance is independent of angle of incidence, the angularly averaged value of $\Delta\Omega$ equals π. Hence, normalised light intensity would be much lower for such a device. Equation (3) in this case reduces to:

$$p = [1 - kT\ln(y+1)/E]\{1 - \ln[(y+1)/y]f/i\} \tag{7}$$

where i is evaluated with the above values of $\Delta\varepsilon$ and $\Delta\Omega$, also with $E = E_G$ and f is a variable close to unity in value, but constrained to the range:

$$1 < f < [1 + 2(kT/E_G) + 2(kT/E_G)^2] \tag{8}$$

This can be deduced by expanding the second part of Equation (1) in terms of Bose–Einstein integrals of order 0, 1 and 2, and noting that the integral of order 0 is highest in value.[18] Again, efficiency arbitrarily close to 100% is obtainable if the light intensity is sufficiently large.

The case where the monochromatic light is obtained by filtering radiation from a blackbody at temperature T_B has been addressed during earlier treatments of two level cells[7], tandem cells[8] and thermophotovoltaic cells.[9] An interesting result in this case is that, if the acceptance angle of the cell is matched to that of the incoming light and the filter reflects emitted light of other wavelengths back to the cell, the open-circuit voltage of the cell equals $E(1 - T/T_B)/q$. More general cases are accommodated by the previous formulation by inserting the appropriate value of $\dot{N}$.

Irreversible entropy $\dot{S}_{\text{irr}}$ production in cells subject to monochromatic light has been discussed elsewhere[10] when the light is from such a filtered blackbody source. Key results are retained in more general cases, notably $d(T\dot{S}_{\text{irr}})/dV = -J$ so that entropy production reaches its minimum value of zero at the open-circuit voltage point. From Figure 2, it is seen that the rate of entropy production therefore decreases almost linearly from short-circuit to the maximum power point, when it then starts decreasing less slowly, becoming zero at open-circuit and then increasing again. As the light intensity increases, the rate of entropy production normalised by the input energy decreases as the maximum power point voltage approaches the open-circuit voltage (Figure 2). Hence, the energy conversion efficiency increasingly approximates a reversible process. At the same time, the equivalent source temperature of the monochromatic light increases. Hence, the energy conversion efficiency progressively approaches the Carnot efficiency of a device operating between an increasingly high effective source temperature and that of the cell, explaining the thermodynamic basis of efficiencies approaching unity.

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