Theoretical limits of photovoltaic solar energy conversion

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ABSTRACT

A largely qualitative survey of solar cell principles is given. Ideas introduced include, the current-voltage characteristic of a p-n junction, the relation between energy gap and conversion efficiency, sad the possibility of increasing these efficiencies by (a) utilizing tandem cells, (b) making us of impact ionization, (c) introducing an intermediate absorber as in thermophotovoltaics.

1. CURRENT-VOLTAGE CHARACTERISTICS

In Fig. 1(a) (Landsberg, 1995) a positive applied voltage moves the current carriers so as to produce a conventional current density (current divided by the cross-sectional area, A say) which flows to the right-hand side. This means electron vacancies ("holes") move to the right as they are positively charged, and electrons to the left as they carry a negative charge. Further, we see that a positive applied voltage yields an easy current flow, i.e. a bigger current density, while the same voltage applied in the opposite direction produces a smaller current density. Our structure has therefore a rectifying property for the current, which is not displayed by a simple resistance, say. The two directions are referred to as 'forward' and 'reverse', and the structure is a rectifier, which is in this case a *p-n* junction. In the figure J_0 is the saturation current density, which is found for reasonably large reverse voltages. For even larger voltages (not shown) the current grows again and the system suffers eventually an electrical breakdown.

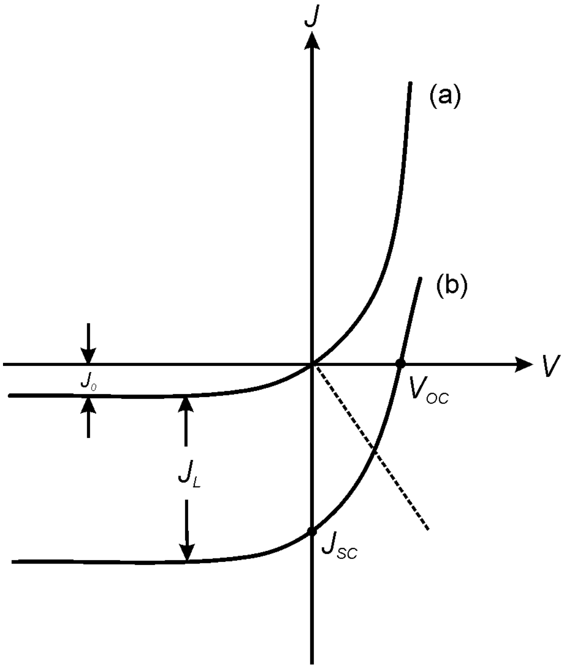

Fig. 1. Schematic current-voltage characteristics of a *p-n* junction:
(a) in the dark, (b) under illumination.

In the presence of light, sunlight in the case of a solar cell, the whole characteristic is displaced rigidly (in the simplest picture) by an amount equal to the light-induced current density J_L, as shown in curve (b). Two new characteristic quantities occur now: the 'open-circuit' voltage V_{oc}, produced in the absence of a current, and the 'short-circuit' current density J_x. Short-circuit means of course that there is then no voltage across the cell. The current AJ_{SC} multiplied by a voltage gives an electrical power as in Ohm's law. In fact, 0.5 $A\ J_{sc}\ V_{oc}$ is a rudimentary measure of the power output of which the cell is capable. It is favoured by (i) a small reverse current density and (ii) a good carrier generation. So far we have considered a unit to which a voltage is applied. In a solar cell, however, the voltage which is developed is generated inside the cell by the electrons and holes which are no longer in equilibrium when the radiation falls on the cell.

2. THEORETICAL EFFICIENCIES

To obtain photovoltaic efficiencies we have to introduce the energy gap E_g across which incident photons can excite the electrons of a semiconductor. They leave behind holes, as already discussed. The electrons and holes are separated in space by the internal electric field of the p-n junction. This yields a photo-voltage and a photo-current.

What is the best value of E_g? If it is zero, all photons can contribute to the photo-current which becomes maximal. The photo-voltage is however zero. A bigger gap stops some photons from producing electron-hole pairs and the photo-current is thereby reduced, while the photo-voltage is increased. Between the limits for the conversion efficiency ($\eta = 0$ for $E_g = 0$ and $\eta = 0$ as E_g tends to infinity) there must lie a value of E_g for which η is maximal - see Fig. 2. This curve assumes a normal solar temperature of about 6000 K and maximum concentration (46500 suns) of the radiation and assuming that the sun surrounds the cell hemispherically. It gives a (theoretical) optimum efficiency of 44% which corresponds to a band-gap of 2.2 kT_p, where T_p is the temperature of the sun ("p" stands for "pump"). This efficiency reduces to about 30% for one sun. Actual efficiencies are of course smaller. They lie near or below 30%, and an improvement by each fraction of one percent results from a real struggle! (de Vos 1992, Sieniutycz and de Vos 2000, Würfel 2000, Kabelac 1994).

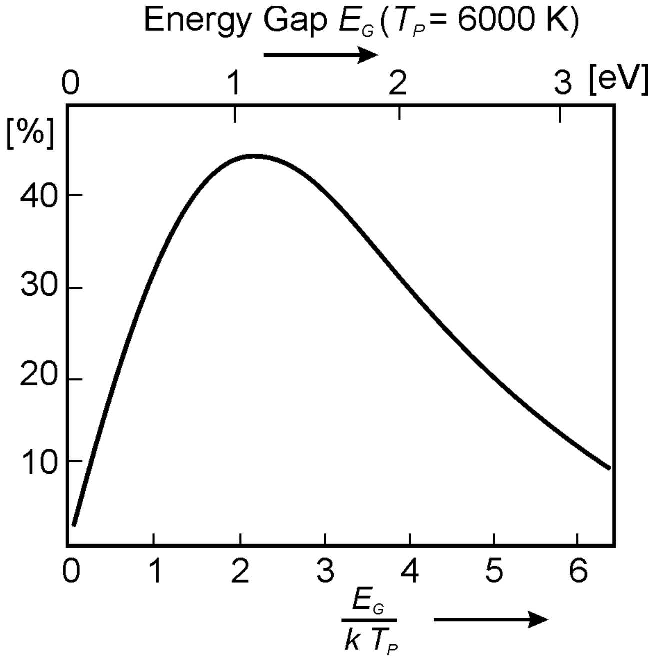

Fig. 2. Energy conversion efficiency as a function of band gap, assuming the pump (i.e. the sun) at 6000 K surrounds the converter.

3. SOME WAYS OF INCREASING EFFICIENCIES

The (theoretical) overestimate of the efficiencies is in part due to the neglect of the natural recombination of electrons and holes which takes place anyway in the presence of a current. It leads to the loss of some electron-hole pairs which can then, not contribute to the current. Thus energy, which should aid the current, is given to the lattice by electron-phonon collisions and to other electrons by the Auger effect (electron-electron collisions). However, the good news is that higher efficiencies can be obtained by having several materials with decreasing energy gaps in series. These systems are called tandem cells. Experimentally one can have so far at most four or five in series. Photons which pass through the first cell (because its energy gap is too big to excite an electron-hole pair), are in this arrangement able to create a pair in the next cell, which has a smaller gap. This is in principle continued down a series of cells to smaller and smaller gaps. The theory can be worked out for an infinite number of tandem cells. This procedure clearly makes better use of the higher energy photons, for if they merely gave up the gap energy to create ONE electron-hole pair, then the remaining energy would go to heat up the lattice, instead of adding to the solar current.

Another way of imagining a use for the higher energy photons is to trace the result if they produce more than one electron-hole pair. This process is called impact ionization, and it takes place in a cell in any case. Instead of producing an electron-hole pair with the energy which is left over being eventually dissipated as heat, it leads to a second electron-hole pair being produced, thus increasing the solar current instead of heating up the sample. This leads to a modification of the theory, and a maximum efficiency can be estimated if this phenomenon is fully exploited. Again one may allow an infinite number of impact ionizations.

Additional electron-hole pairs can also be produced by the re-absorption of emitted photons (“photon recycling”). This is, another process which takes place automatically in a cell. These two extreme cases, the infinite tandem cell and unlimited impact ionizations, lead, remarkably, to similar values of the theoretical maximum efficiency. For one sun illumination it is of the order of 61%-68%, and it is about 86%-88% for maximal solar concentration, depending on the method of calculation. The result is higher than the value of 44% of section 2, reflecting the improvements resulting from the tandem connection and/or the impact ionizations. Nothing like these values have been obtained experimentally, of course, but they give an indication of what can still be aimed at; for a review, and for a list of about 100 theoretical and experimental efficiencies, see Landberg and Badescu (1998).

The experimental results are the lower ones in this list. Even for monochromatic irradiation the efficiency drops already to 45%. This is a favourable case, since to design a cell for what is in effect just one narrow frequency range is so much more straightforward than to cater for the whole of the solar spectrum.

For a two-stage GaAs/GaSb tandem cell with a concentration ratio of $C = 50$ suns one can achieve the very respectable efficiency of 34%. The value for an InP/GaInAs cell has been reported at 32%. For small area GaAs/GaInAsP tandem cells at $C = 39.5$ one has found 30%. For unconcentrated radiation one can reach 25% for a GaInP/GaAs/Ge cell. So one can give many values for the efficiency (Landsberg and Badescu, 1998). Note that the maximum concentration is about 46500 suns. In satellites solar cells represent a small fraction of the total expense, so that expensive cells can here be used. But among additional considerations: one needs in these cases a long life and good radiation resistance. A major market share has been secured by GaAs-Ge monojunctions, and one is looking forward to 25% efficient triple junctions', 40% cells are envisaged in the more distant future. In these space cells one can tolerate a medium beginning-of-life efficiencies provided they deteriorate only marginally to end-of-life efficiencies by virtue of good irradiation stability.

4. THE HETEROJUNCTION WITH AUGER EFFECTS

Recall that in radiative studies one should include with radiative emission also absorption of radiation, since one cannot occur without the other. In fact, they are related by the important principle of detailed balance. lf one applies this idea to impact ionization one tends an analogous symmetry. One would expect electron-hole recombination with the energy set free being given to, say, a conduction band electron. This removes particles which might contribute to the solar current and, like radiative recombination, it is detrimental. This recombination, named after Pierre Auger, is the detailed balance analogue of impact ionization, and should therefore be included in a theory which takes account of impact ionization, though this has not always been done. In our work in this area we have always insisted on using a probability $P(E)$ that an electron which has the energy E to impact ionise will actually do so. This introduces unfortunately another parameter, but a simple theory serves as a guide to its value. In a simple model we find theoretically that for $P = 1$ the efficiency of a cell is lowered by 5% if Auger recombination is included, but only by 3% if both Auger recombination and impact ionization are covered. The theory introduces quite a few parameters, apart from the obvious ones like diffusion coefficients, effective densities of states, lifetimes of electrons and holes, etc. For there are threshold parameters for Auger recombination since a partner electron, making a transition between bands, cannot do so from the bottom of the band owing to constraints of energy and momentum conservation.

A broad conclusion is that band-band Auger effects shift the optimum energy gaps of both heterojunction materials to higher values, but this is opposed by impact ionization. Favourable solar cell efficiencies may be expected for good impact ionization, low radiative and Auger recombination and thin active layers. Specific designs of cascaded cells may get further improved results (Andreev, 1999, and Aroutiounian *et al.,* 2001).

5. THERMOPHOTOVOLTAICS

The average energy of absorbed sold photons is normally of the order of 1.9 eV, whereas the semiconductor band gap is typically 1 eV. This leaves an average of 0.9 eV per incident photon to be absorbed by the lattice as heat, and therefore essentially wasted. This waste is decreased if the solar radiation is first taken up by an intermediate absorber whose temperature is less than the solar temperature and which acts now as a “low-temperature sun”. The 0.9 eV average energy loss is now decreased and the overall conversion is increased. In this so-called thermophotovoltaic conversion the average energy of the photons emitted by the absorber, and then of course absorbed by the cell, is less than 1.9 eV and implies a smaller heat loss by thermalisation. This leads to improved efficiencies.

6. CONCLUDING REMARKS

It is worth noting that it has been estimated that the energy payback time of a solar cell is of the order 3 to 4 years and in its lifetime a cell may produce something in the order of 10 times its cost of production (Knapp and Jester, 2001). This shows that it can be a satisfactory device on purely economic grounds.

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