Solar cell as a self-oscillating heat engine

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SUMMARY

A solar cell, also called a photovoltaic cell, is a device that converts the energy of light into an electrical current. Although the earliest solar cells date from the 19th century, the theoretical account of their operating principles remain somewhat unsatisfactory. Though surprising, this is not without precedent in the history of science: practical steam engines were built long before the formulation of the laws of thermodynamics. One might also note that airplanes are much older than a satisfactory theory of lift on an aerofoil.

In general, a solar cell structure consists of an absorber layer, in which the photons of incident radiation are efficiently absorbed resulting in the creation of electron-hole pairs. In order to separate the photo-generated electrons and holes from each other, the so-called *semipermeable membranes* are attached to the both sides of the absorber.

However, as pointed out by the expert [1]:
We frequently read that it is just the electric field of a pn-junction which supplies the driving force for the currents flowing during illumination [. . .] In fact something must be wrong in our physical education, if we think that a DC current can at all be driven in a closed circuit by a purely electrical potential difference. The word potential alone should tell us that no energy can be gained by moving a charge along any closed path.

Some authors claim that not the electric field but rather the gradient of electrochemical potential is an actual driving force similarly to the case of battery. However, this argument cannot be complete either, because the same objection to an electrostatic potential driving the cyclical DC applies also to a static chemical potential. There is also a fundamental difference between a battery, which when generating current is slowly relaxing to an equilibrium state in which it can no longer generate a voltage difference, and a solar cell, which is a heat engine, capable of steadily generating voltage and current as long as it remains in contact with two heat baths at different temperatures.

In a heat engine a working substance undergoes a sequence of transformation such that, after a full cycle, it has absorbed more heat from a bath at a higher temperature than the heat that it has rejected into a bath at a lower temperature. The net energy gained powers the *self-oscillation* of what we shall generically call the piston (even though this might not always correspond to what an engineer would ordinarily think of as a piston). This piston may, in turn, drive an external load. Though this has not usually been stressed in the scientific literature, the self-oscillation of the piston is an essential part of operation of heat engines that run automatically, without some external agent performing the necessary modulation. It is the self-oscillatory dynamic that allows an engine to convert a non-periodic source of power (such as heat, which simply flows from high to low temperatures) into work outputted at another, well-defined frequency. A physically oriented theory of self-oscillation may therefore provides a useful perspective on thermodynamic problems [2].

An independent approach to quantum thermodynamics and quantum engines suggests also that all engines should contain an oscillatory mechanism usually described by a time-dependent Hamiltonian. This aspect is missing in the standard theory of solar cells but the model presented in [3] seems to be difficult to accept by the community. Therefore, for pedagogical reasons, I discuss first a simple hydrodynamical model which can be treated as a close analogue of a solar cell. This is a water pump powered by the "putt-putt boat" engine. Here, self-oscillations of the water level in the tank, induced by the external source of heat (flame) and a positive feedback mechanism, act like a piston which pumps water in the external water circuit in the direction determined by suitable valves.

The typical semiconductor solar cell consists of a moderately doped p-type absorber, on both sides of which a highly doped layer is formed, n-type on the front side and p-type on the back side, respectively . The electron gas in the n-type layer is separated by a thin depletion region from the p-type absorber. The position of this border is a main dynamical variable describing self-oscillations in the cell. Namely, as always in such a situation where free electrons are confined by the background positive charges, one expects the emergence of collective macroscopic charge oscillations with a plasma frequency. Such oscillations in the THz domain were observed in pn-junctions by several experimental groups.

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The collective oscillatory motion of a relatively dense electron gas (or rather quantum fluid) in the n-type layer can be described by a single degree of freedom - the position of its boundary. The self-oscillations of this boundary are powered by the energy of an incident light with the help of a suitable positive feedback mechanism, similarly to oscillations of the water level in the “putt-putt boat” engine. Then, the charge oscillations are transformed into a DC current by a diode property of the pn-junction. Again, this mechanism corresponds to the action of valves in the hydrodynamical model.

Similar models based on self-oscillations and positive feedback can explain the operating principles of thermoelectric generators [4], fuel cells and “biological engines”. An open problem is to design and perform experimental tests of the presented theory. In principle, such tests could be based on the detection of weak THz radiation emitted by a working photovoltaic cell or resonance phenomena stimulated by the external THz modulation.

References

[1] P. Wuerfel, *Physics of Solar Cells. From Principles to New Concepts*, (Wiley-VCH, Weinheim, 2005)

[2] A. Jenkins, Physics Reports **525**, 167 (2013)

[3] R. Alicki, D. Gelbwaser-Klimovsky, K. Szczygielski, J. Phys. A: Math. Theor. **49** (2016) 015002

[4] R. Alicki, J. Phys. A: Math. Theor. **49** (2016) 085001