

Approaching Tandem Solar Cells in Chemistry Classes

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Abstract Protecting the climate by increasing the share of energy from renewable sources, such as solar energy, has become a central goal of the EU. Hence, this contribution presents approaches to implement this important topic into chemistry education. It first summarizes the working principles of silicon and perovskite solar cells and describes the potential of combining them within a so-called tandem solar cell. We then present an experiment suitable for student laboratories in which a working perovskite solar cell is constructed using anodically oxidized titanium and copper(I) thiocyanate coated FTO glass as electrodes. The self-built solar cell is also experimentally compared to commercially available silicon solar cells. Finally, we provide practical suggestions for covering solar cells in chemistry classes.

Keywords: *perovskite solar cells, silicon solar cells, tandem solar cells, renewable energy*

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1. Introduction

In order to protect the climate, the EU targets to drastically increase the share of energy from renewable sources [1], although resources (e.g., silver) for technologies like solar cells are rare [2]. One approach to tackle this problem is to improve the energy efficiency of solar cells. However, the common silicon solar cells already almost reach the theoretically possible energy efficiency [3]. For this reason, current research focuses on new promising types: perovskite and tandem solar cells.

In this article, we provide schematic representations of the operating principle of different solar cell types simplified for high school students. Moreover, we present related theoretical basics and experiments in which high school students can build a perovskite solar cell themselves and compare it with a silicon solar cell.

The perovskite solar cell is built with anodic oxidized titanium sheets as one of the electrodes instead of commonly used FTO glass, which can be beneficial for photovoltaic devices because titanium is more ductile and has a higher fracture toughness than FTO glass [4]. From an educational point of view, it is valuable that the presented experiment can build a bridge between semiconductor physics and electrochemistry and thereby between chemistry and physics lessons. In addition, it could effortlessly be integrated into a whole teaching unit on renewable energies, as anodic oxidized titanium can be used in several other school experiments, e.g., on photocatalysis and sodium ion batteries [5].

2. Theoretical background

In the following, the working principle and the theoretical energy efficiency limit of silicon solar cells are explained. Furthermore, the operating principle of perovskite solar cells and the combination of both solar cells in a so-called tandem solar cell are described.

2.1. Silicon solar cell

Nowadays, silicon solar cells are widely used. Silicon can be amorphous, polycrystalline, and monocrystalline, but monocrystalline silicon solar cells are favorable, because they have the highest energy efficiency [6]. Commercially available panels can have energy efficiencies up to 24 % and a lifetime of 25-30 years [7]. The disadvantage of silicon solar cells is that the purification of silicon is energy-intensive and expensive, even though costs have been reduced over the last decades [8].

2.1.1. Working principle

The electronic band structure of silicon has a gap between the conduction and the valence band that classifies it as semiconductor. The replacement of silicon atoms with atoms from the third and fifth main group in the Periodic Table of the Elements creates p-type and n-type doped silicon, respectively. In comparison to undoped silicon, p-type misses one valence electron / contains one hole and n-type has an additional valence electron per impurity atom (Figure 1a). Contacting both types of doped silicon in a p-n junction leads to the movement of electrons (illustrated as blue filled circles) from the n-type to the holes (shown as black circles) of the

p-type and, in consequence, to the formation of an electric field in a so-called space-charge region [9].

If the two types of doped silicon are illuminated with light whose energy equals at least the energy difference between the conduction and valence band / the band gap energy of silicon, electron-hole pairs (also called excitons) are generated. Due to the electric field electrons and holes created in the space-charge region move towards electrode and counter electrode in opposite directions and produce an electrical potential [9].

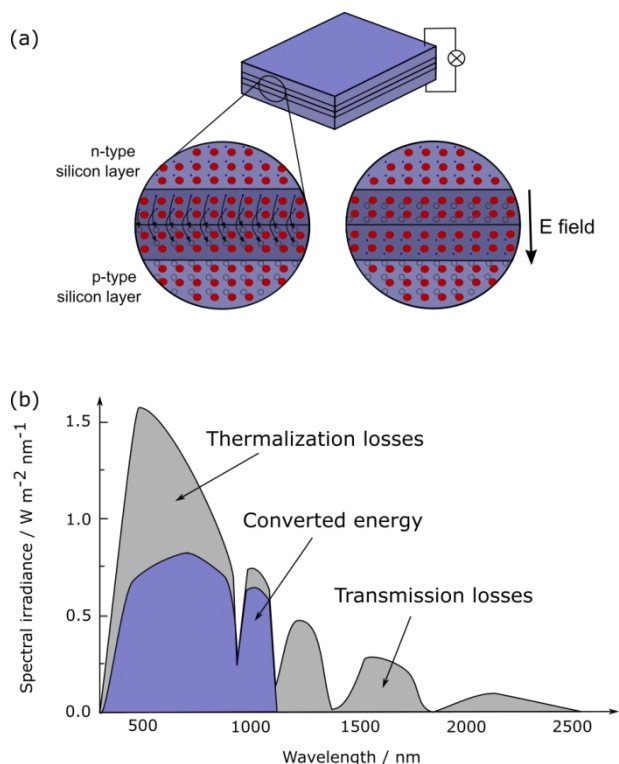


Figure 1. a Working principle of silicon solar cells [9], b schematic drawing of plot of sunlight energy per time, surface area and wavelength over wavelength: the grey area represents the incoming sunlight energy per time and surface area and the blue area the energy per time and surface area that can be converted by silicon solar cell [10].

2.1.2. Theoretical energy efficiency limit

When sun energy is converted into electric power by silicon solar cells, two main energy losses occur (Figure 1b): On the one hand, one part of the sunlight spectrum, short-wave light, has more energy than required to create an exciton and the energy excess is converted into heat (thermalization losses). On the other hand, long-wave light has not enough energy to create an exciton and therefore transmits through silicon without being harvested (transmission losses). Thus, the energy efficiency of a silicon solar cell has a theoretical limit. Approximately one third (30 %) of the sun energy can be converted [11].

A semiconductor with a band gap of 1.34 eV would offer the best compromise between thermalization and transmission losses. It would allow the highest energy efficiency (33 %) that is possible with a single p-n junction (this theoretical maximum is called the Shockley-Queisser limit) [11]. Silicon has a band gap size (1.1 eV) that is close to this optimum.

2.2. Perovskite solar cell

Central element of a perovskite solar cell is a material with a perovskite crystal structure (Figure 2a). The advantage is that these materials and the solar cell fabrication are low-cost. Challenging is the stability of perovskite solar cells [12].

2.2.1. Working principle

The working principle of a perovskite solar cell is similar to the one of a silicon solar cell (Figure 2b) [13]: Energy-rich sunlight excites the green displayed perovskite so that excitons form. Due to diffusion, electrons and holes move through the perovskite to an electron and a hole transport layer (illustrated in pink and red), respectively. These layers then transport them to electrodes so that the electrons can finally flow from one electrode through an electric device to the other.

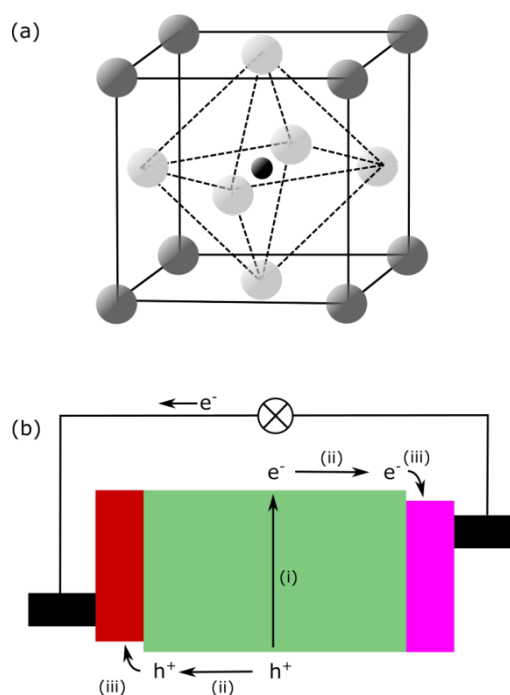


Figure 2. a Perovskite crystal structure ABX_3 ; Element A in dark grey, B in black and X in light grey (cubic structure is shown, but can also be tetragonal and orthorhombic), b Working principle of perovskite solar cells: (i) Formation of excitons after light absorption by the perovskite layer (green), (ii) diffusion of charge carriers, (iii) transport of electrons and holes to the electrodes (black) by electron transport layer (pink) and by hole transport layer (red), respectively [13].

2.2.2. Combining perovskite with silicon solar cell

The band gap of perovskites (1.6.-1.8 eV [14]) is higher than the optimum band gap of 1.34 eV (section 2.1.2). Therefore, thermalization losses are low, but transmission losses are high. The opposite is true for silicon solar cells, as its band gap (1.1 eV) is lower than 1.34 eV. Combining both solar cells to one tandem solar cell can allow both the low thermalization losses of perovskite solar cells and the low transmission losses of silicon solar cells if the perovskite solar cell is located at the top and the silicon solar cell at the bottom [10,14]. Then, the perovskite cell absorbs UV light and visible light with less thermalization losses than the silicon one (Figure 3a and b), because the

difference between the energy of the absorbed light and the band gap energy is not as big as it is in case of silicon (Figure 3c). IR light transmits through the perovskite cell and would get lost, if there was not the silicon cell underneath which harvests the IR light (Figure 3a). The record for tandem solar cell efficiency made of perovskite and silicon is 33.7 %, whereas currently the highest efficiency of a silicon solar cell is 26.1 % [6]. Following the idea behind the tandem solar cell and combing several solar cells to one makes efficiencies up to 39.2 % possible and up to 47.6 % when sunlight is concentrated [6].

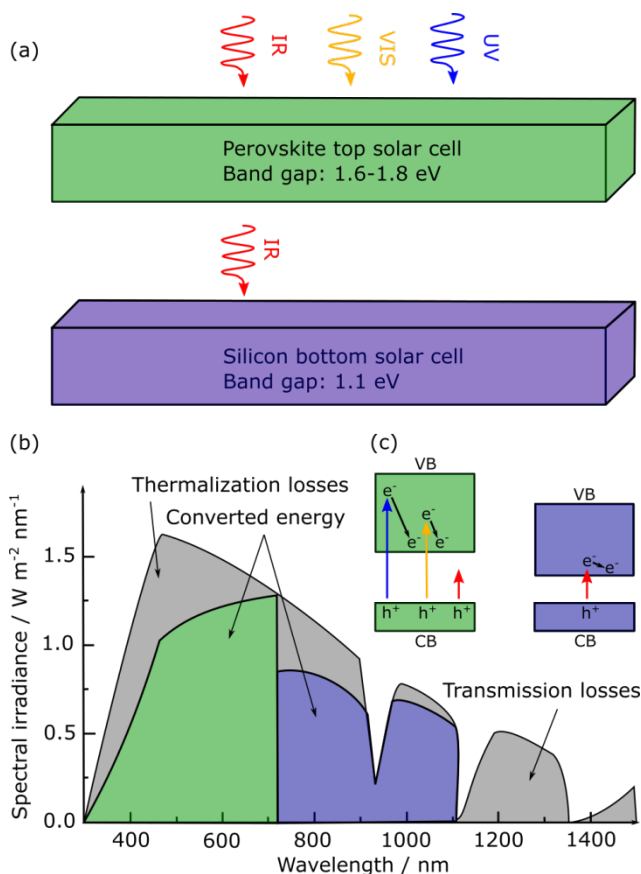


Figure 3. a Working principle of tandem solar cells, b Schematic drawing of plot of sunlight energy per time, surface area and wavelength over wavelength: the grey area represents the incoming sunlight energy per time and surface area, the green area the energy per time and surface area that is converted by perovskite solar cell and the blue area the one that is harvested by silicon solar cell, c Band structure with valence band (VB) and conduction band (CB) of perovskite (green) and silicon (blue): UV and visible light energy are higher than the band gap energy of perovskite, whereas IR light energy is not, but it is higher than the band gap energy of silicon [10,14].

3. High school student experiment

3.1. Building a perovskite solar cell

This section presents the construction of a working perovskite solar cell suitable for use in a student laboratory setting. The procedure is adapted from an article by Patwardhan et al. who created a perovskite cell by coating an FTO glass step by step with the individual layers of titanium dioxide, perovskite and copper(I) thiocyanate (hole conductor). The perovskite used is methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$). Applying a

carbon powder layer and a second FTO glass results in the working solar cell [15].

We use the same chemicals, but modify the process in two ways: (1) Instead of coating an FTO glass with titanium dioxide by treating it with titanium isopropoxide, we create a nano-porous titanium dioxide layer on a titanium sheet by anodic oxidation. Similar electrodes have been discussed in literature which lists benefits such as better mechanical stability and use of low-cost manufacturing processes like roll-to-roll processing [4]. (2) Patwardhan et al. distribute the material for the coatings using a glass pipette. We use a self-built spin coater for this, which consists of 3d printed parts and a computer fan (Figure 4a and b, building instructions can be supplied on request). This allows for a thinner and more even distribution of the coating material.

3.1.1. Fabrication of nano-porous TiO_2 layer

The electron-conducting titanium dioxide layer is produced by anodic oxidation of titanium. A more detailed description of the experimental setup and further applications of the resulting nano-porous titanium dioxide was already published by Lanfermann et al. [5].

Equipment: voltage source, cables, alligator clips, stand material, beaker (100 mL), large crystallizing dish.

Chemicals: Titanium sheets, ammonium fluoride (GHS06), ethylene glycol (GHS07, GHS08), 1 M calcium chloride solution (GHS07), acetone (GHS02, GHS07).

Procedure: An electrolysis apparatus is set up using two titanium sheets as electrodes. A solution consisting of ammonium fluoride (0.5 wt-%) and distilled water (1.0 wt-%) in ethylene glycol is used as electrolyte. The titanium is anodized at 50 V DC for 45 minutes. Afterwards, the sheet is cleaned by immersion in the calcium chloride solution and the beaker is rinsed with the calcium chloride solution to bind fluoride ions.

Observation: During the anodizing process, the sheet initially shows changing color impressions for a few seconds but appears increasingly dull as the experiment progresses. After rinsing and drying, a dull, brownish layer can be seen on the titanium sheet (Figure 4c).

Interpretation: The resulting brownish layer is nano-porous titanium dioxide, which can be several μm thick. The thickness depends on the duration of the anodizing process. More details about the growth mechanism can be found in the previously cited paper [5].

3.1.2. Fabrication of the solar cell

On top of the previously prepared titanium dioxide, the other layers can now be applied to complete the perovskite solar cell.

Equipment: FTO glass, hot plate, Eppendorf pipette, snap-cap jar, adhesive tape (standard/double-sided/heat-resistant), multimeter, cables, alligator clips, tweezers, lamp (Osram Ultra Vitalux 300 W), spin coater, nitrile gloves.

Chemicals: lead(II)-chloride (GHS07, GHS08, GHS09), methylammonium iodide (GHS07), Dimethyl sulfoxide (DMSO), copper(I) thiocyanate (GHS09), dipropyl sulfide (GHS02, GHS07), carbon (powdered), anodized titanium sheet.

Safety instruction: Working with lead salts requires the use of a fume hood and nitrile gloves.

Procedure: Before continuing construction of the perovskite solar cell, two solutions need to be prepared.

Perovskite solution: Dissolve 105 mg lead chloride and 172 mg methylammonium iodide in 0.75 mL DMSO with stirring.

Copper(I) thiocyanate solution: Dissolve 6.1 mg copper(I) thiocyanate in 1 mL dipropyl sulfides with stirring at approximately 70 °C. The dissolution process can take 1-2 hours.

The part of the titanium sheet not coated with an oxide layer is covered with heat-resistant adhesive tape (Figure 4c). The sheet is then attached onto the spin coater with double-sided adhesive tape. Using the Eppendorf pipette, 45 μ L of the perovskite solution is dripped onto the titanium oxide layer, carefully spread around and spin coated for about 30 seconds with the spin coater being operated at 12 V DC (Figure 4b). The titanium sheet is then heated to 100 °C using the hot plate until the coated layer has turned dark brown (5-10 minutes) (Figure 4d). After cooling down, the coating process is repeated with the copper(I) thiocyanate solution. The cooled sheet is then covered with an even layer of carbon powder (approximately one large spatula tip) (Figure 4e). Finally, the FTO glass is placed over the oxide layer in a staggered manner and the construction is fixed in place using adhesive tape, taking care to leave enough space for alligator clips to be attached (Figure 4f). Afterwards, the manufactured perovskite solar cell is connected to the multimeter and irradiated onto the FTO glass side using the lamp to measure voltage and current.

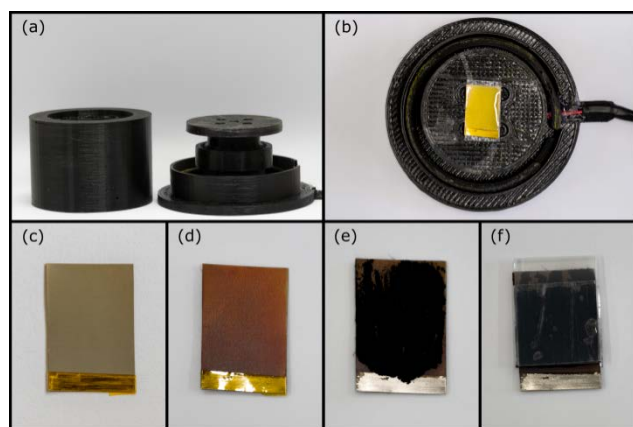


Figure 4. a Self-built spin coater, b Fixed sheet covered with perovskite solution before spin coating, c Titanium sheet with oxide layer covered with heat-resistant adhesive tape, d Sheet after heating, e Sheet covered with carbon powder, f Finished perovskite solar cell.

3.2. Comparison between silicon and perovskite solar cell

The larger band gap size of the perovskite compared to silicon can be shown by an experiment. The use of a filter which blocks light with higher energy than IR demonstrates that this low energy radiation can only be used by the silicon solar cell.

Equipment: filter glass (Schott long-pass-filter RG-1000), lamp (Osram Ultra Vitalux 300 W), Silicon solar cell, perovskite solar cell, cables, alligator clips, black cardboard, knife, multimeter.

Procedure: A hole with the size of the perovskite solar cell is cut in the black cardboard. The solar cell is then connected to the multimeter and covered with the cardboard, with the hole directly above the solar cell (Figure 5). The hole is closed with another piece of cardboard and the construction is irradiated with the lamp, measuring voltage and current. Then, the covering piece of cardboard is replaced with the filter glass and measurements are repeated. Finally, the solar cell without the cover is illuminated and measured. This process is repeated with the silicon solar cell.

Observation: In a sample measurement, the silicon solar cell only shows small drops in the measured voltage when it is covered with the filter glass instead of being exposed to the lamp light, whereas the current declines by almost 80%. With the perovskite solar cell, the voltage, by contrast, drops to just almost 30% of the initial value, while the current is halved. It should be noted, however, that these values are almost identical to the values measured while covered with the cardboard. Data from sample measurement can be found in the Supplemental Information.



Figure 5. Experimental setup for the comparison between silicon and perovskite solar cells.

Interpretation: Measurements have shown that the filter glass used completely filters out all wavelengths below 820 nm. Our perovskite has a band gap of 1.58 eV, which corresponds to a maximum wavelength of approx. 785 nm needed to trigger a photovoltaic effect [16]. Silicon, on the other hand, has a band gap of 1.1 eV and an associated maximum wavelength of approx. 1100 nm. The filter glass therefore has only a comparatively small effect on the silicon solar cell, whereby the lowering of the current intensity is related to the fact that the filter glass also lowers the intensity of the transmitted wavelengths considerably. The wavelengths transmitted by the filter glass are too low in energy to produce a photovoltaic effect in the perovskite solar cell; accordingly, the current and voltage drop.

4. Educational Perspectives

The working principle of a silicon solar cell is a common subject in K-12 physics education, encompassing the fundamental principles of semiconductors, doping and

doping techniques, and the transformation of light or photons into usable electrical power. Within the context of the ongoing renewable energy discourse, the theoretical efficiency limit of silicon solar cells may serve as motivation for exploring alternative solar cell types not only in physics but also in chemistry class. Aside from elucidating the fundamental working principles of these cells, such as the dye-sensitized solar cell or the described perovskite cell, it is reasonable to address the applied materials, their spectral properties, as well as the effects of energy losses resulting from thermalization and transmission on their power generation. A central learning goal for the students should be the reasons for the combination of solar cell types to tandem solar cells, as a possibility of increasing efficiency, as described in section 2.2.2. In this context, the experiment in 3.2 can demonstrate that the self-built perovskite solar cell, in contrast to the silicon solar cell, generates almost no voltage in the IR range. In addition to this effect, other differing properties of silicon and perovskite solar cells should also be discussed. This includes, for example, their energy amortization, stability, and the extent to which they can be integrated into sustainability cycles such as the circular economy [17].

5. Conclusion

The topic of solar cells is not only suitable for physics lessons. The experiments presented in this article enable teachers to also cover it in chemistry lessons within the context of electrochemistry. Future research projects in the field of physics or chemistry education should focus on the development of further experiments that address tandem solar cells since those are very promising to achieve a sustainable energy future.

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