Novel hybrid thermal-photovoltaic device based on fluorescent heat pumping

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In a conventional solar cell, the solar photon current is converted to work solely by the generated electro-chemical potential of electron and holes. Any light-induced temperature rise due to the inherent electron-hole pair thermalization is not only un-useable by an ideal photovoltaic cell, but is also a major efficiency decrease factor. Here, we suggest a novel concept for a conversion of sunlight into electricity through thermally enhanced photoluminescence (PL), which recycles thermal energy to useful work and allows exceeding the shockley-Queisser (SQ) limit for a single bandgap photovoltaic (PV) cell. A thermally insulated low band-gap photo-luminescent material absorbs the incoming solar photons and emits light, which is characterized by both its high temperature (T) and the optically excited chemical potential (μ). Photoluminescence materials, such as rare earths, can conserve their quantum efficiency at high temperatures[1]. When temperature rises each emitted photon carries away also thermal energy. The hot photo-luminescence is subsequently harvested by a secondary higher band-gap solar cell operating at room temperature. The detailed balance shows that such combination benefits from both the high photon-current of the low band-gap absorber, and the high voltage of the high band-gap PV, which yields conversion efficiencies as high as 68% (depending on the absorber and cell bandgaps), at practical operating temperatures.

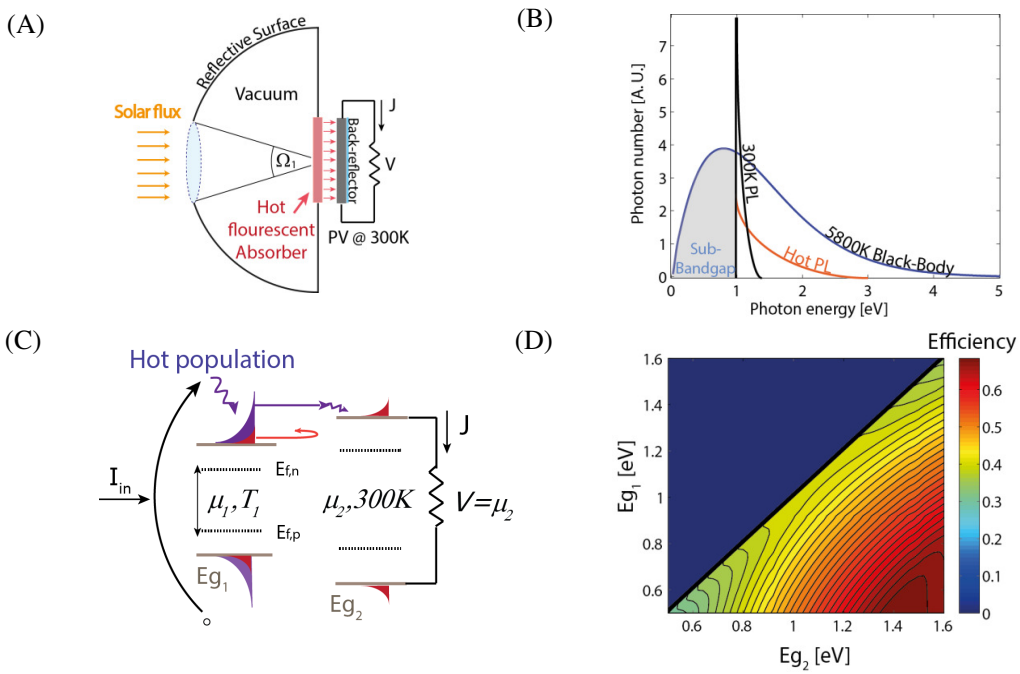

Figure 1. The device's scheme (A) Illustration of the thermally enhanced PL Vs. the solar spectrum and room temperature PL (B) The absorber/cell energies and current flow (C) and the 2D efficiency map dependence on the absorber and the PV band-gaps, Eg_1 & Eg_2 (D)

Figure 1A shows the devices scheme, where incoming sunlight excites the photo-luminescent absorber. Photon recycling is achieved by limiting the absorber's angle of emission[2], while emitted photons below Eg_2 are reflected back to the absorber by the cell's back reflector. The qualitative differences between room-temperature PL and hot PL are shown in 1B, where the temperature increases the average energy of each emitted photon. Figure 1C illustrates the

higher PV cell bandgap needed for the conversion of hot PL, and the current flow. The calculated efficiencies are presented in figure 1D, where maximal efficiency is found to be over 68%, under full photon recycling conditions. A more detailed understanding of the hybrid photo-thermal conversion mechanism is gained by analyzing the device I-V curves, depicted in figure 2A. The three curves are calculated for different absorber-cell bandgap combinations: Eg_1 equals 0.5 eV, and Eg_2 varies between 0.5 eV, 0.8 eV, and 1.3 eV. The photon recycling ratio is equivalent to a concentration factor of 1000. The first I-V curve (red) shows a remarkable feature of this concept. It is "double humped" and includes two maximal power points (mpp): a "hot" and "cold" ones. While the first (hot) exceeds the corresponding SQ limit for Eg=0.5eV with η=49.7%, the second is equal to the SQ limit at 25% efficiency. The reason for the efficiency enhancement is clearly the current enhancement which contributes to the larger "hump". When Eg_2 is increased, this current enhancement vanishes and replaced by the open-circuit voltage enhancement that leads to maximal efficiency of 62.5% at the cold mpp (blue curve). Figure 2B shows the change in absorber's temperature and chemical potential as a function of the operating voltage at Eg_1=Eg_2=0.5 eV. As one can see, a transition of the operating conditions occur at V=0.38V, where the temperature drops sharply while the chemical potential increases. The physical reason for this dependence is the recombination current emitted by the PV cell towards the absorber. Since the PV cell is at 300K, its photon current is characterized by a cold temperature, meaning, spectrally narrower than the hot absorbers emission (inset in 2B). At low operating voltages, in similarity to short circuit, the chemical potential cannot build up and remains zero. Thus, the absorber is a pure black-body, characterized only by its temperature and step-function emissivity. Photon-number is not conserved at this regime, and photon current is enhanced in order to satisfy energy conservation, leading to the "hot" mpp. The operating conditions under this regime are similar to the solar-thermal PV concept suggested by Wurfel[3]. When voltage increases the chemical potential builds up due to the recombination current emitted by the PV cell (similarly to open circuit conditions at an ideal PV). For μ>0, quantum efficiency (QE) plays an important role[4]. By the detailed balance, the only way to conserve energy under QE=1 is when each emitted photon also carries thermal energy, which lowers the operating temperature dramatically. The result is the cold mpp which does not benefit from the current enhancement, but from the voltage enhancement depending on the PV cell bandgap, Eg_2. The excessive thermal energy in each emitted photon can be harvested by increasing the Eg_2 above Eg_1 (Fig. 1C, and blue green curves in 2A). In this case the extracted energy benefits **from both the high photon-current of the low band-gap absorber, and the high voltage of the high band-gap PV, which yields conversion efficiencies as high as 68%, at practical operating temperatures.**

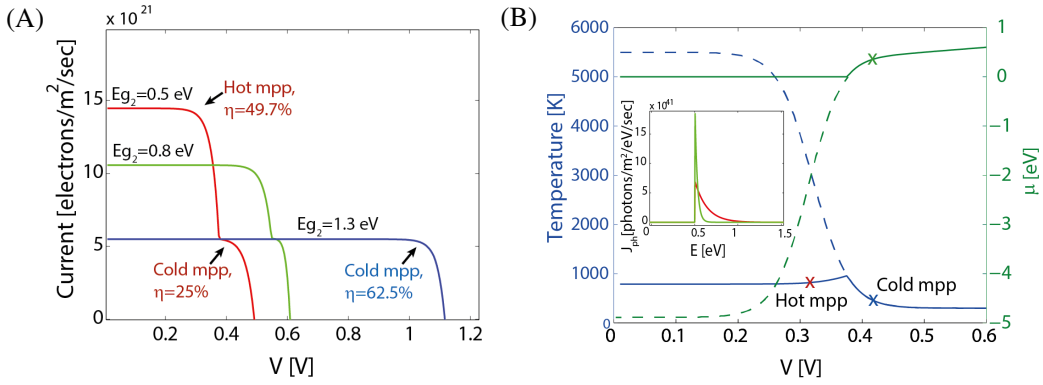

Figure 2. The I-V curves corresponding to a 0.5 eV absorber and three PV cell values of (0.5 eV, 0.8 eV and 1.3 eV) (A) The temperature/chemical potential dependence on the PV cell voltage (B). (Inset: comparison of the hot absorber and the cold cell spectra)

In order to experimentally demonstrate this thermodynamic model, we apply photon current to induce chemical potential and additional heat current to control the thermal load of a PL system. Specifically, we study the fluorescence of Neodymium (Nd^{+3}) doped glass under 532 nm excitation. The heat current is supplied by a CO_2 laser (Fig. 3A). The PL is measured by a calibrated spectrometer. Figure 3B shows the power spectrum at various CO_2 pump intensities, while figure 3C shows the total number of emitted photons bellow 1μm. Evidently, as we increase the thermal load, the PL exhibits a blue-shift evolution. This is shown by the reduction at the 900nm emission peak and enhancement of the 820nm emission peak (Fig. 3B) while photon number is conserved (green solid lines at Fig. 3C). This trend continues until reaching the transition point. As we increase the heat current even further the power spectrum and the number of emitted photons increases sharply at all wavelengths (dotted lines in Fig 3B and red line in 3C). In addition we monitor the operating temperature by Fluorescence Intensity Ratio Thermometry (FIR)[5] (Figure 3C, inset). Above the transition point we observe sharp increase in temperature. This is a clear transition to thermal regime where conservation of photon number does not apply. In addition, we examine the cooling effect through FIR measuring of the temperature while switching the 532nm excitation and keeping the CO_2 intensity constant. Figure 3D shows the power spectrum when the 532nm excitation in turned on and off. The reduction in operating temperature by the 532nm excitation can be seen by the change in the ratio between the 820nm and 900nm peaks, corresponding to a decrease of temperature from ~1700K to ~1400K, as expected by the thermodynamic model.

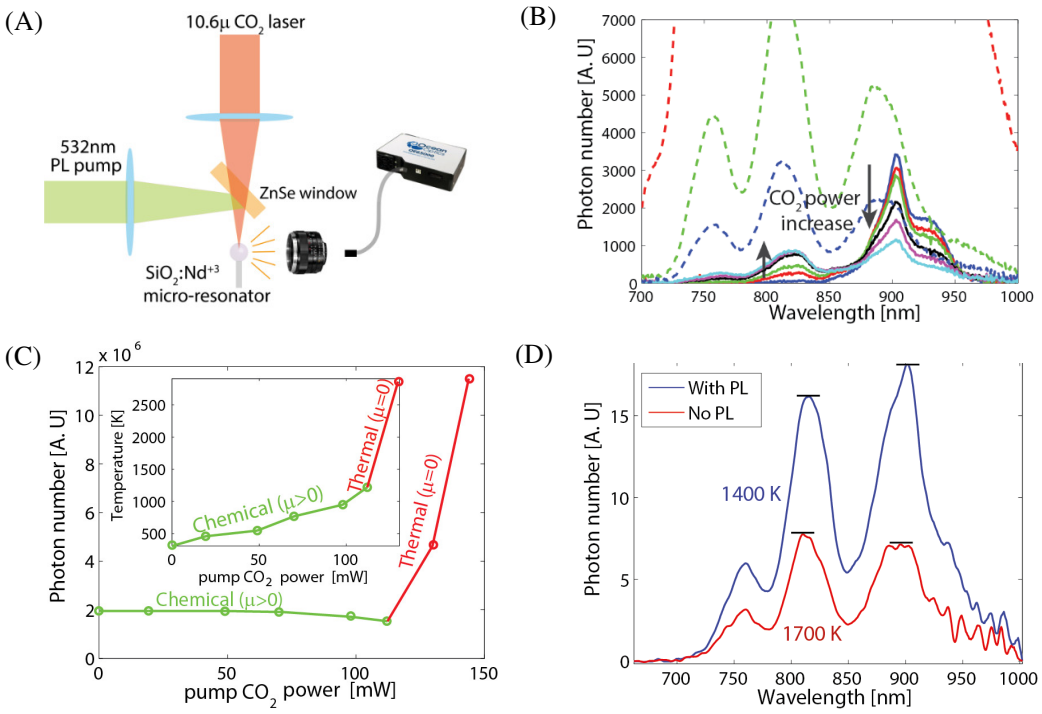

Figure 3. Experimental setup (A) PL spectra evolution with CO_2 power increment (B) photon number and temperature dependence on CO_2 power (C) and hot vs. cold spectrums

To conclude, a novel concept for efficient conversion of solar energy, based on thermally enhanced PL and photon recycling has been presented. An experimental proof of concept agrees well with our thermodynamic model, exhibiting operating temperatures that are considerably lower than in thermal-PV. This opens the way for new sensitization materials that are durable in these temperatures and allow enhanced conversion of solar energy

References

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