A Sunlight Cooling Device
Based on a 2D van der Waals Heterojunction

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Introduction

The quantum yield (*QY*) defines the number of electron-hole pairs generated in a semiconductor (gap E_g) by the absorption of a photon of energy $h\upsilon$. In the simplest model we have $QY=1$ when $h\upsilon>E_g$. However, $QY>1$ occurs when the excess energy generates extra electron-hole pairs by Coulomb carrier-carrier interaction. This is the impact ionization (II) behaviour [1]. In the ideal case, shown in Fig. 1, a photon of energy $h\upsilon>nE_g$ gives $QY=n$ (with n a n integer). Recent works show that, due to large Coulomb screening, II is particularly strong in few-layers transition metal dichalcogenides (TMD) [2].

In a previous study, we used *ab initio* calculations to compute the electronic band structure of MoS_2/WSe_2, a van der Waals heterojunction based on monolayers of TMD. The absorption coefficient is shown Fig. 2. The gap of this heterojunction is small since E_g=0.4 eV [3]. Here, we show that in contact with a large bandgap reservoir (Fig. 3), under solar radiation and considering an ideal II, it is possible to cool this small gap heterojunction. The sun light generates electron-hole pairs with a large kinetic energy, involving a strong II. The consequence is an accumulation of carriers at the band edges. This excess of carriers can be extracted in a well-designed reservoir by absorbing phonon. We then obtain an evaporative cooling.

Model

To model the carriers in the heterojunction, we assume that their distribution function is a Fermi function at temperature T_c with a difference between the Fermi levels of electrons and holes given by $\Delta\mu=\mu_c-\mu_v$, where μ_c (μ_v) is the Fermi level of electrons (holes) in the conduction (valence) band. To calculate T_c and $\Delta\mu$, we consider a detailed balance model:

$$\begin{cases} J_{gen} = J_{rec} + J_{contact} \\ P_{gen} = P_{rec} + P_{contact} + P_{phonon} \end{cases}$$

We present the different terms of this equations in Fig. 4. J_{gen} is the carrier flux generated by the sun light, considering the absorption of the heterojunction (Fig. 2) and an ideal II. J_{rec} is the recombination flux, considering both radiative and non-radiative recombinations. $J_{contact}$ is the flux of carriers between the heterojunction and the reservoir. P_{gen}, P_{rec} and $P_{contact}$ are respectively the power flux-densities corresponding to the fluxes J_{gen}, J_{rec} and $J_{contact}$. P_{phonon} is the exchanged power between the carriers and the phonons and is assumed proportional to the difference of carrier and phonon temperatures [4]. When the carrier temperature T_c<300 K, the carriers absorb phonons and $P_{phonon}<0$. If this heat absorption is greater than the heat emitted by the non-radiative recombination, the heterojunction is cooled. We define the cooling efficiency as:

$$\eta_{cooling} = \frac{-P_{phonon} - P_{rec,non\ rad}}{P_{gen}}$$

Results

Fig. 5 shows the temperature T_c as a function of E_{cv}, the gap of the reservoir. We get T_c<300 K ($P_{phonon}<0$) if both E_{cv}<0.98 eV and the II is considered. The detailed balance equation shows that P_{phonon} is more negative as $P_{contact}$ is larger. $P_{contact}$ is proportional to the flux of extracted carriers, multiplied by the extraction energy. The II increases the number of carriers and the energy increases with E_{cv}. Nevertheless, if E_{cv} is too high, the flux is reduced. The best trade-off is obtained for E_{cv}=0.85 eV. As shown Fig. 6, where $\eta_{cooling}$ is represented versus E_{cv}, this corresponds to a maximum efficiency of 61%.

Conclusion

We propose a cooling device which uses the sun as the only source of energy. This concept could have practical applications in nanoscale cooling.

References

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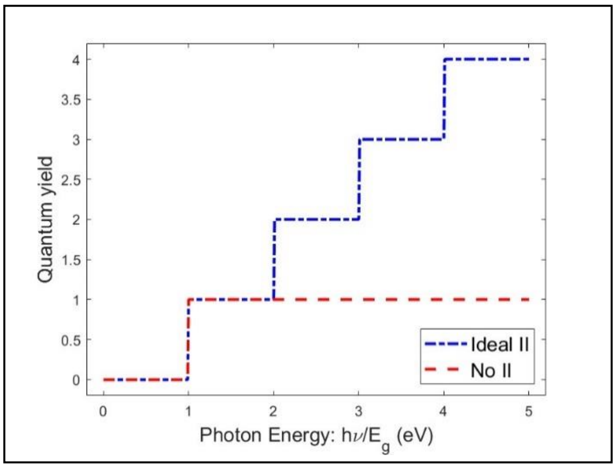

Fig. 1. The quantum yield (QY) is shown as a function of $h\nu/E_g$ where $h\nu$ is the photon energy and E_g is the gap of the semiconductor. The blue curve shows the QY under ideal impact ionisation (II) and the red curve shows the QY without II.

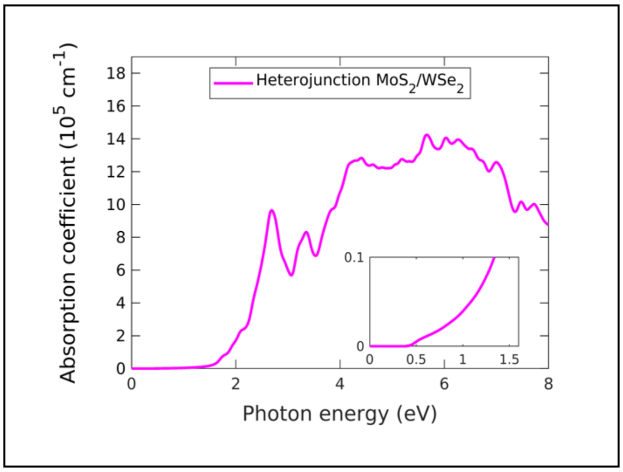

Fig. 2. Absorption coefficient of the MoS_2/WSe_2 heterojunction, computed with DFT calculation. The inset plot is a zoom in the low energy range.

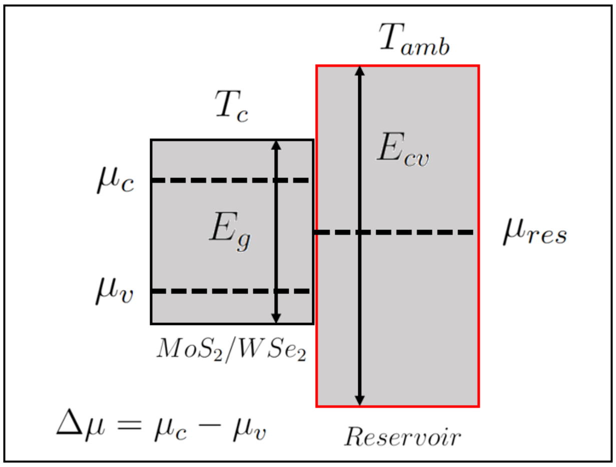

Fig. 3. Band diagram of our device where the MoS_2/WSe_2 heterojunction (bandgap $E_g = 0.4$ eV) is in contact with a reservoir (bandgap $E_{cv} \geq E_g$). μ_c (μ_v) is the Fermi level of electrons (holes) in the conduction (valence) band. μ_{res} is the Fermi level in the reservoir. T_c is the carrier temperature in the heterojunction. $T_{amb} = 300$ K is the ambient temperature.

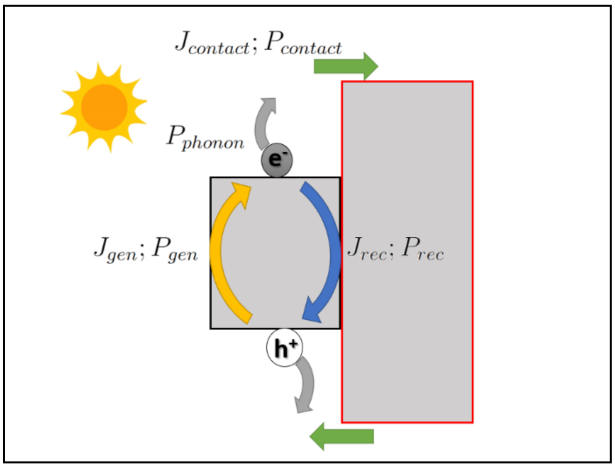

Fig. 4. Carriers fluxes and power flux densities displayed on the band diagram of the device. We consider an isolated system. Thus, carrier exchanges occur only between the small gap heterojunction and the reservoir.

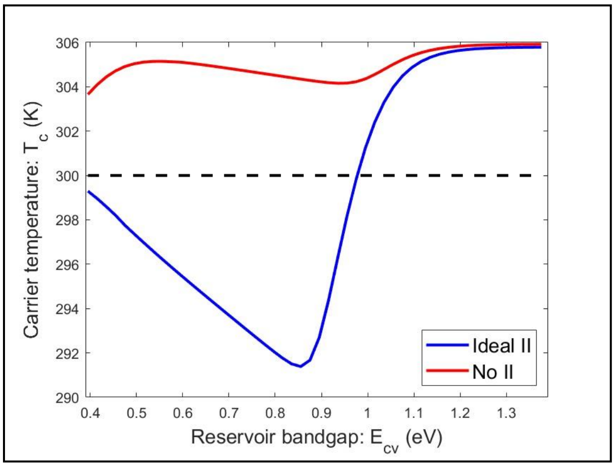

Fig. 5. The carrier temperature T_c is shown with ideal (blue curve) and without (red curve) II, as a function of the reservoir bandgap E_{cv}. The black dashed line stands for $T_c = 300$ K.

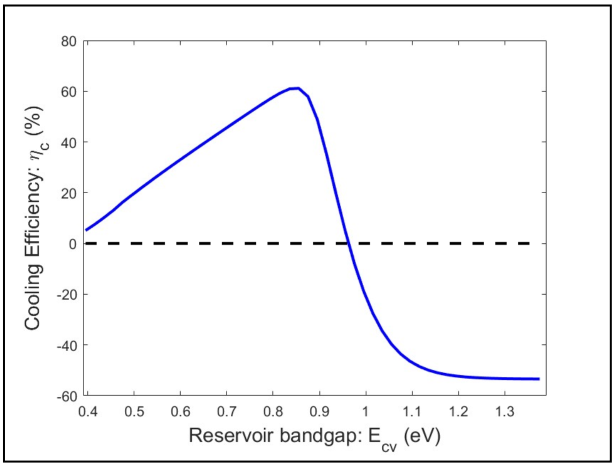

Fig. 6. The cooling efficiency $\eta_{cooling}$ is shown with ideal II as a function of the reservoir bandgap E_{cv}. The black dashed line stands for $\eta_c = 0$ %.