Photovoltaic Efficiency Enhancement through Thermal Up-Conversion.

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The limiting efficiency of a photovoltaic device that employs luminescent up-conversion of sub-band-gap light has recently been calculated, indicating a substantial efficiency enhancement can be achieved [1]. Typically, a luminescent up-conversion process involves the absorption of two photons, but ambient thermal energy can be harnessed to yield a one photon up-conversion process, through the same effect that is used to achieve laser cooling [2].

In figure 1, the data points represent the luminescence spectrum resulting from laser illumination at 1.35eV of a QW p-i-n photodiode[1] at open-circuit. The spectrum shows emission both below the laser excitation energy (Stokes emission) and above the laser excitation energy (anti-Stokes emission). It is convenient to denote the photon flux due to the Stokes emission as X and the flux due to the anti-Stokes emission U; the optical processes are illustrated in the inset of figure 1. The anti-Stokes emission is of particular interest as it corresponds to photons whose energy has been increased through the removal of heat from the lattice. This effect has been demonstrated in a number of materials and arises from a thermal Fermi-Dirac distribution of carriers being established in both the QW and barrier, with the characteristic temperature of the lattice. The anti-Stokes emission from this process has traditionally been exploited in laser cooling experiments [2], but here it is applied to yield an increased photovoltaic efficiency.

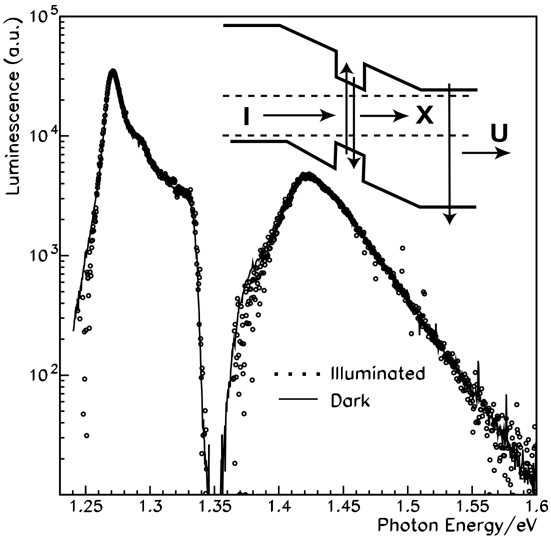

Fig 1. *Emission spectra from a single QW p-i-n diode (QT458) at 296K. The points indicate the luminescence measured under QW illumination at open circuit. The solid line indicates the luminescence measured in the dark but at an applied bias equal to the open-circuit voltage (Voc=0.8V) obtained under illumination. The inset shows the optical processes in the structure; I represents the incident photon flux, X represents the QW radiative recombination and U represents the barrier recombination.*

Before proceeding to discuss the photovoltaic application of this effect, it is important to consider the role of the solid line in figure 1, representing the luminescence obtained with no laser excitation, but with an applied bias equal to the open-circuit voltage. The equivalence between the luminescence under open-circuit and dark injection establishes that the same quasi-thermal equilibrium established under electrical injection in the dark, is also established under QW illumination. This implies excellent carrier transport must exist, both in and out of the QW and justifies the use of quasi-Fermi levels to describe the luminescent processes [3].

[1] Note that the absence of data around 1.35eV is due to a holographic notch filter that was used to attenuate the laser.

In a traditional, single junction solar cell, sub-band-gap sunlight cannot be absorbed and is wasted. However the anti-Stokes emission demonstrated above, can be used to couple the sub-band-gap sunlight to the ambient thermal reservoir, thereby increasing the photon energy of some of the incident sub-band-gap photons by a few kT. The anti-Stokes photons therefore represent a one-photon, thermal up-conversion process and provide a means for enhancing the efficiency of a photovoltaic device.

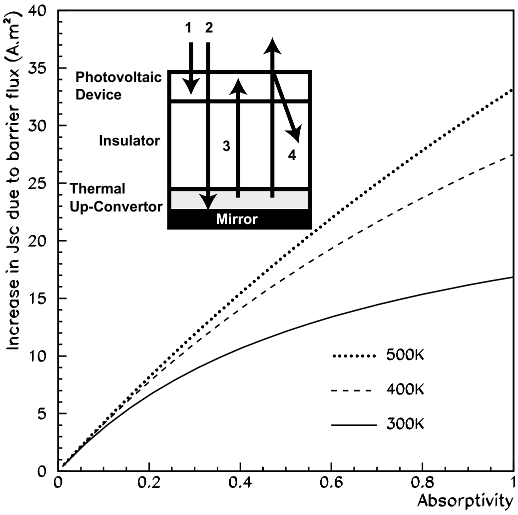

Fig. 2. *Increase in PV short-circuit current (Jsc) as a function of QW absorptivity for a GaAs PV device. The inset shows the optical processes in a typical up-conversion PV device.*

Photovoltaic up-conversion devices have typically employed the structure depicted in the inset of figure 2. A conventional PV device is located at the top of the structure and is separated from the up-convertor by a transparent electrical insulator. Here the up-convertor is described in terms of a QW p-i-n device operating at open-circuit, but the concept is quite general and may be applied in a variety of materials. The requirements are first, an absorption of photons below that of the PV device and second, a thermalisation process that allows the photogenerated carrier distribution to equilibrate with the lattice temperature. The PV device will absorb high energy photons (ray 1), leaving sub-band-gap photons to proceed through the transparent insulator (ray 2). Some of the sub-band-gap photons will be absorbed in the QW and lead to the splitting of the quasi-Fermi levels in the QW device, resulting in QW and barrier emission. It is then possible to arrange the QW device such that the barrier emission is absorbed in the upper PV device (ray 3), yet for the PV device to remain transparent to QW emission (ray 4). In essence, the QW structure couples the thermal energy of the lattice to sub-band-gap photons. Of those sub-band-gap photons that are absorbed in the QW, a fraction U are re-radiated at a sufficiently high photon energy to allow them to be absorbed by the PV device.

The photogeneration in the QW layer is the product of the QW absorptivity a and the black-body solar flux at temperature 5759K filtered by the PV device that absorbs to its band-edge. Figure 2 shows how the increase in short-circuit current due to the up-converted barrier photon flux, varies as a function of QW absorptivity and p-i-n diode temperature. The calculation is based on an ideal GaAs PV device of band-gap 1.42eV at a fixed temperature of 300K. The QW p-i-n up-convertor has an absorption edge at 1.32eV and variable temperature. The entire structure is assumed to have a refractive index of 3.62. With increasing QW absorptivity, the fraction of up-converted photons U decreases. However, the high degree of light trapping due to the refractive index partly compensates for this effect, so with increasing QW absorptivity, the increase in QW photogeneration due to the incident solar flux, ensures that the greatest increase in short-circuit current and therefore efficiency, occurs with unity QW absorptivity. At 300K, the efficiency of a radiatively dominated GaAs PV device rises from 30.0% for a bare p/n cell to 31.3% when the QW p-i-n device is located beneath the p/n junction. If a temperature difference exists, such that the QW thermal up-convertor is at an elevated temperature, while the PV device remains at 300K, then an efficiency of 32.6% is obtained for a QW up-convertor temperature of 500K.

[1] T.Trupke, M.A. Green & P.Würfel, J. Appl. Phys. **92** (7) p4117-4122, 2002

[2] C.E. Mungan & T.R. Gosnell, Advances in Atomic, Molecular and Optical Physics, **40**, p161-228, 1999

[3] P.Würfel, J Phys C, **15** (18), p3967-3985, 1982