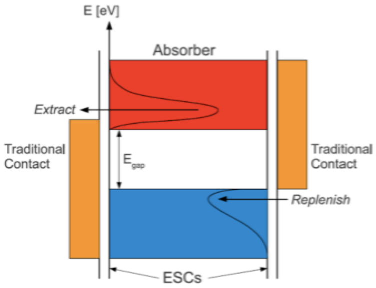
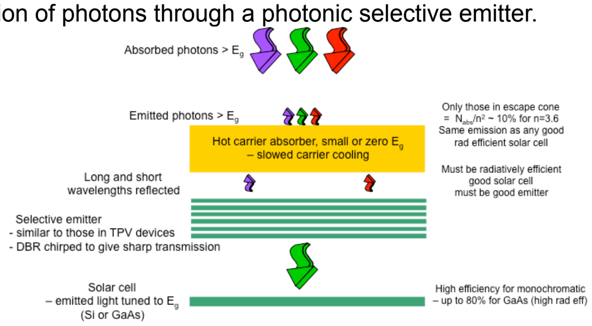
HOT CARRIER SOLAR CELLS FOR EXTRACTION OF HIGH ENERGY CARRIERS

Gavin Conibeer, Santosh Shrestha, Shujuan Huang, Robert Patterson, Hongze Xia, Yu Feng, Jianfeng Yang, Neeti Gupta, Suntrana Smyth, Yuanxun Liao, Simon Chung, Zhilong Zhang, Martin A Green
School of Photovoltaic and Renewable Energy Engineering, University of New South Wales Australia
Sydney, New South Wales 2052, Australia

1 INTRODUCTION

The Hot Carrier solar cell (see Fig. 1) is a Third Generation device that aims to tackle the carrier thermalisation loss after absorption of above band-gap photons. It is theoretically capable of efficiencies very close to the maximum thermodynamic limit. It relies on slowing the rate of carrier cooling in the absorber from ps to ns. This challenge can be addressed through nanostructures and modulation of phonon dispersions. Extraction of carriers whilst they are still hot can be carried out either through narrow band electronic contacts or by emission of photons through a photonic selective emitter.





2 SLOWED HOT CARRIER COOLING

The key property for a hot carrier absorber is to slow the rate of carrier cooling from the picosecond timescale to at least 100s of ps. Hot carriers cool primarily by emission of longitudinal optical (LO) phonons [,]. The general properties of phonons and carriers required of a hot carrier absorber have been defined [ ]. Materials which exhibit a phonon bottleneck, which reduces loss of energy into phonon modes, have demonstrated higher carrier temperatures. Reduced dimension nanostructures have also shown slowed carrier cooling and higher carrier temperatures, again it is summarised by restriction of carrier-phonon and phonon-phonon interactions. Elastic extraction of the energy of these hot carriers to an external circuit can be achieved electrically by only collecting carriers above a certain energy using energy filters which either require extraction over a barrier of restrict extraction to a narrow range of energies (energy selective contacts. Alternatively optical extraction of these high energiescan be achieved by engineering high rates of external radiative recombination and then collection of the radiation through a narrow optically selective emitter by a conventional solar cell, as first suggested by Farrell [ ].

3 HOT CARRIER ABSORBER

The absorber consists of a semiconductor with narrow electronic band gap. This allows absorption of a wide range of photon energies and hence gives a high current for the device. For an ideal device at 1 sun the highest efficiency of 65% is given for a band gap of 0.7eV.[9] This optimum band gap decreases as concentration ratio increases, all the way to zero at maximum concentration and the efficiency rises to 85%. In both cases the efficiencies are very close to the ideal limiting efficiency for an infinite tandem cell, 66% and 86.8% respectively. They are slightly lower because of the slightly lower degree of freedom in thermal populations of carriers. [9]

The absorption of the wide spectral range of solar photons results in the generation of non-equilibrium populations of electrons and holes. These hot carriers would normally thermalize to their respective band edges in a very short time, of the order of ps. The hot carrier cell absorber needs to reduce this carrier cooling rate, such that carriers can be extracted whilst still hot and hence give a higher voltage for the cell.

4 HOT CARRIER COOLING

For the majority of semiconductor materials the ‘hot’ carrier population of photogenerated electron-hole pairs has most of the energy of the absorbed photons in the hot electrons, because of the small effective mass of electrons as compared to holes. Hence the following discussion primarily considers electrons. Hot hole dynamics are qualitatively similar but, as their energy is much lower, are less important for the overall extraction of energy from the device.

The oscillating electric field of these hot electrons interacts with the valence electron shell around atoms as the hot electron passes through the lattice, causing the valence electrons and the atom cores to oscillate out of phase. This will occur at a particular resonant frequency of the atomic lattice, i.e. the zone centre longitudinal optical (LO) phonon energy. The hot electron loses a discrete amount of energy in this process – the LO phonon energy. It cools by emission of a series of these LO phonons. The momentum change on LO phonon emission is small because of the steep band of hot electrons, hence it is only LO phonons at zone centre which have an appreciable energy such that optical phonon emission is the most efficient electron energy loss mechanism. In polar semiconductors electrons couple to LO phonons via the Frölich mechanism. This predominant electron cooling by emission of LO phonons results in the build-up of a non-equilibrium (hot) population of optical phonons. If this population is relatively long lived, hot phonons can transfer their energy back to electrons via further reciprocal scattering events. This will effectively slow the rate of further carrier cooling and is known as the 'phonon bottleneck' effect. Hence the critical factor in determining whether a phonon bottleneck can slow the rate of carrier cooling is the rate of decay of 'hot' optical phonons. The main decay mechanism for LO phonons is via the Klemens mechanism in which two acoustic phonons of half the energy and equal and opposite momenta are emitted.

5 SLOWED CARRIER COOLING IN MQWS

Low dimensional multiple quantum well (MQW) systems have also been shown to have lower carrier cooling rates. [,] Comparison of bulk and MQW materials has shown significantly slower carrier cooling in the latter. Bulk GaAs as compared to MQW GaAs/AlGaAs materials measured using time resolved transient absorption by Rosenwaks [5], have been recalculated to show effective carrier temperature as a function of carrier lifetime by Guillemoles [ ]. This shows that the carriers stay hotter for significantly longer times in the MQW samples, particularly at the higher injection levels by 1½ orders of magnitude. This is due to an enhanced 'phonon bottleneck' in the MQWs allowing the threshold intensity at which a certain ratio of LO phonon re-absorption to emission is reached which allows maintenance of a hot carrier population to be reached at a much lower illumination level. More recent work on strain balanced InGaAs/GaAsP MQWs by Hirst [6] has also shown carrier temperatures significantly above ambient, as measured by PL. Increase in In content to make the wells deeper and to reduce the degree of confinement is seen to increase the effective carrier temperatures.

6 CONCLUSION

Materials exhibiting mechanisms that can slow carrier cooling are challenging. Hot carriers cool by emission of optical phonons that subsequently decay into acoustic phonons, i.e. heat in the lattice. The lifetime of these optical phonons can be extended by establishing a phonon bottleneck whereby phonons scatter their energy back to hot carriers, keeping them hot long enough to be extracted.

Multiple nano-well materials exhibit slower carrier cooling, probably through localisation of carriers and emitted phonons leading to a phonon bottleneck. Compounds with a large mass difference between constituent atoms exhibit large phonon band gaps that should block the decay of optical phonons and also promote phonon bottleneck.

A combined multiple nano-well (MNW) structure utilising wells with large phononic band gaps is suggested as a structure which can maximise the phonon bottleneck caused by all these mechanisms to slow carrier cooling, and hence give hot carrier lifetimes long enough to be extracted to the external circuit at high voltage.

A radiatively efficient hot carrier absorber illuminating an efficient solar cell through a narrow band pass selective emitter can lead to high overall conversion efficiencies of the hot carrier energy. Such an optically coupled device removes the need for good electronic transport in the absorber and allows separate optimization of optical and electrical performance.

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