HOT CARRIERS EFECTS IN SOLAR CELLS: harvesting energy from non-equilibrium states

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1 INTRODUCTION

The Hot Carrier solar cell (see Fig. 1) aims to tackle the carrier thermalisation loss after absorption of above band-gap photons. It has the potential to achieve very high efficiencies in a device that is essentially a single junction. Detailed balance calculations indicate limiting efficiencies as high as 65% under 1 sun and 85% under maximum concentration [ ]. However a series of modelling developments has shown that as real material parameters are introduced the predicted efficiencies decrease. What emerges is that maximisation of the thermalisation time constant for hot carriers is critical to improved efficiency [ ].

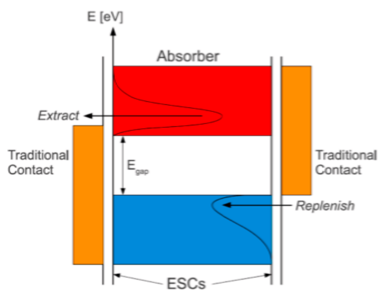

Figure 1: Hot Carrier cell: carriers remain at elevated temp. in absorber and are extracted through narrow contacts at high V.

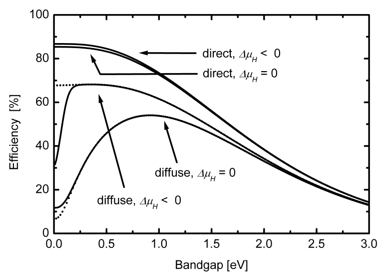

Figure 2: Ideal detailed balance efficiencies for the HCSC as a function of absorber band gap, for both 1 sun (diffuse) and maximum concentration (direct) illumination and for the two models Ross and Nozik ($\Delta\mu < 0$) and Wurfel ($\Delta\mu = 0$). After Green [1]

2 HOT CARRIER COOLING: MECHANISMS AND MATERIALS

The carrier cooling mechanisms are investigated and depend primarily on emission of optical phonons by cooling carriers, predominantly electrons. Under some circumstances these optical phonons can be produced at such a high density that they cannot decay away fast enough and a ‘phonon bottleneck’ is formed that allows the phonon energy to scatter back with the electron ensemble thus re-heating it. Creating the conditions for this phonon bottleneck seems the most fruitful route for significantly increasing the thermlaisation time constant.

Quantum well nanostructures exhibit such phonon confinement with significantly high carrier temperatures. The reasons for this are not completely clear but are affected by the restriction of hot carriers diffusing in the direction perpendicular to the wells and by confinement of phonons in the wells. Prevention of decay of optical phonons into acoustic phonons is another method for maximising phonon bottleneck. Materials with a large difference in acoustic and optical phonon energies can block this Klemens’ route for phonon decay. A range of materials are identified as having these properties with the principle requirement that there is a large mass difference between their constituent atoms. Some of the most promising are III-nitrides, especially InN, and their analogues, which include transition metal nitrides – of which HfN and ZrN are most interesting - and group IV compounds – of which SnSi has the most impressive modelled properties. Experimental demonstration of these effects is very limited at present although there are encouraging signs that these properties will soon be demonstrated in several material groups. Attempt has been made to investigate The hot carrier dynamics have been investigated in multiple quantum wells with time resolved photoluminescence and in hafnium nitride HfN using ultrafast TA spectroscopy. Initial results suggests a few nanoseconds thermalisation time in HfN which is very encouraging.

3 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 [ ], 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 [ ] 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.

4 CONTACTING TO HOT CARRIER CELLS

Contacting to hot carrier cells requires specific contacts that only allow transmission of a narrow range of energies. This is so that cold carriers in the contacts do not cool carriers in the absorber. The most promising route to such contacts at present is the double barrier resonant tunnelling structure which can be tuned to specific energies. Such structures in high quality have been made in III-Vs and demonstration of resonant tunnelling achieved. Thin film structures involving silicon and oxides have also shown promising proof of concept. An alternative to electrically contacting is to allow the hot carrier absorber to stay at open circuit and re-radiate photons from hot carriers recombining. Such an approach requires an optically selective filter to illuminate a high efficiency conventional solar cell and has the advantage that optical and electrical properties can be optimised in separate structures.

5 COMPLETE HOT CARRIER DEVICES

Combination of absorbers and contacts in full devices has yet to be realised. But there are now a number of designs for such combinations and the next few years should see their fabrication and demonstration of full proof of concept of these challenging but highly promising hot carrier devices.

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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