

RECENT PROGRESS WITH HOT CARRIER SOLAR CELLS

Martin A. Green¹, Gavin Conibeer¹, Dirk König¹, Santosh Shrestha¹, Shujuan Huang¹, Pasquale Aliberti¹, Lara Treiber¹, Robert Patterson¹, Binesh Puthen Veetil¹, Andy Hsieh¹, A. Luque², A. Martí², P.G. Linares², E. Cánovas², E. Antolín², D. Fuertes Marrón², C. Tablero², E. Hernández², J-F. Guillemoles³, L. Huang³, T. Schmidt⁴, R. Clady⁴, M. Tayebjee⁴

¹ARC Photovoltaics Centre of Excellence, University of New South Wales, Sydney, Australia, 2052
Tel: +61 2 9385 4018 Fax: +61 2 9662 4240 email: m.green@unsw.edu.au

²Institut Energie Solar-Universitat Polytechnica Madrid; Avenida Complutense s/n – 28040 Madrid, Spain
Tel: +34 915441060 Fax: +34 915446341 email: luque@ies-def.upm.es

³Institute for Research and Development of Photovoltaic Energy (IRDEP), joint EDSRC-CNRS, Paris Scientifique et de l'École Nationale Supérieure de Chimie de Paris, 6 quai Watier, F-78401 Chatou, France
Tel: +33 1 5542 6381 Fax: +33 1 4427 6750 email: jf-guillemoles@enscp.fr

⁴School of Chemistry, University of Sydney, Sydney Australia, 2006
Tel: +61 2 9351 2781 Fax: +61 2 9351 3329 email: t.schmidt@chem.usyd.edu.au

ABSTRACT: Hot carrier solar cells offer one of the most promising options for high performance “third generation” photovoltaic devices. For successful operation, these need to be thin, strongly absorbing, radiatively efficient devices in a simple 2-terminal configuration. Nonetheless, they offer potential performance close to the maximum possible for solar conversion, equivalent to a multi-cell stack of six or more tandem cells possibly without some of the limitations, such as spectral sensitivity. However, hot carrier cells offer some quite fundamental challenges in implementation that our team is addressing in an internationally collaborative effort.

1 INTRODUCTION

The likely cost-efficiency regimes of “first generation” wafer-based silicon technology as well as that of “second generation” thin-film cells is shown in Fig. 1. First generation devices presently have manufacturing costs of about US\$200/m² and module efficiency of about 14% (140 Wp/m²), giving about \$1.40/Wp manufacturing costs for large manufacturers [1]. The best thin-film devices on the other hand have manufacturing costs of about \$100/m² and module efficiency around 10% (total area) giving manufacturing costs of about \$1.00/Wp (including overhead [1]). If manufacturing costs similar to thin films can be retained while targeting 74% efficiency rather than 31% limit for conventional cells, considerable leverage is obtained in reducing the manufacturing cost as shown by the “third generation” region (III) in Fig. 1. Values in the \$0.20-\$0.50/Wp range would result from manufacturing costs per unit area similar to those already demonstrated for conventional thin films.

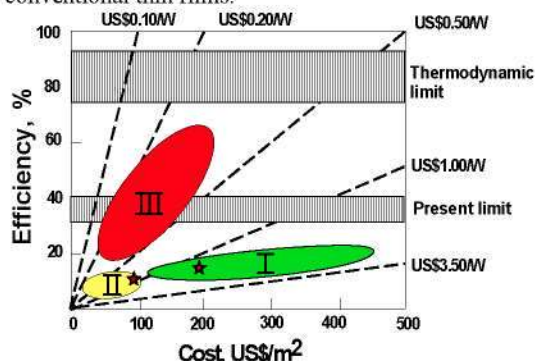


Figure 1: Cost/efficiency regimes for the three generations of PV technology discussed in the text [2].

A range of technologies that are capable of exceeding the conventional PV cell limit are shown in Fig. 2. The highest efficiency, at least for a time-symmetric system [2], is obtained for an infinite tandem stack of cells of different bandgap. However, very similarly efficiencies are possible for hot carrier cells, higher in principle than from a 6-cell stack that may correspond to a practical limit on the number in a stack. If this is accepted, the hot carrier cell is arguably the highest efficiency cell concept yet suggested.

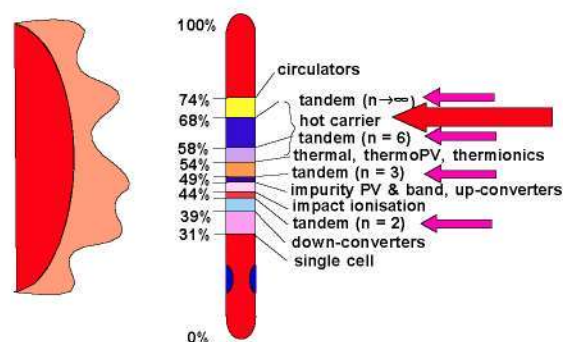


Figure 2: Third generation options [2].

2 HOT CARRIER CELL PRINCIPLES

In a normal cell, a lot of energy is lost through relaxation of photoexcited carriers to energies close to the bandgap (Fig. 3). A high energy blue photon produces the same overall outcome as a lower energy red photon due to this relaxation. In a hot carrier cell, this relaxation is avoided by one method or another, allowing energy in excess of the bandgap to be stored in the photoexcited carrier populations.

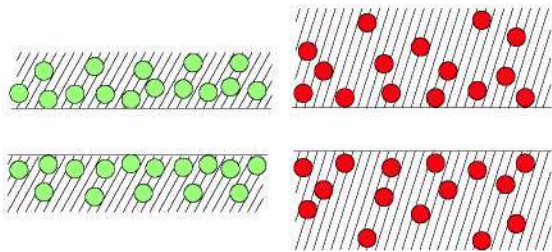


Figure 3: “Cold carrier” versus “hot carrier” populations.

The efficiency limits on this approach can be calculated by an extension of the original Shockley-Queisser approach [3,4] as shown in Fig. 4. The uppermost curve labeled ① represents results of an analysis by Ross and Nozik [3] while that labeled ② represents results from Würfel’s analysis [4]. The dashed line shows the conventional “cold carrier limits”.

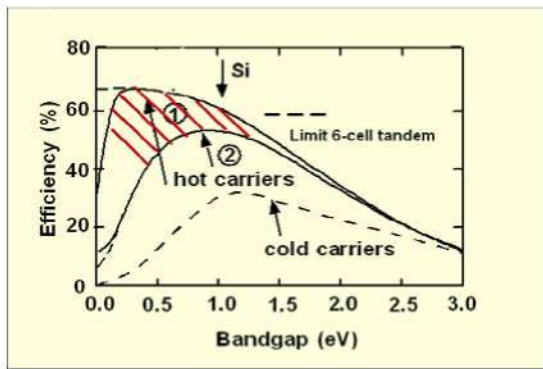


Figure 4: Limiting efficiency versus bandgap for hot and cold carrier devices.

Ross and Nozik’s analysis assumes radiative recombination only (zero Auger recombination) whereas Würfel’s assumes infinite Auger recombination (This is not as bad as it sounds since Auger recombination is not an energy loss process for an ideal hot carrier cell!). If Auger recombination is regarded as an intrinsic material property, the limit would rely between these extremes suggesting efficiency limits above a 6-cell tandem may well be possible for material of selected bandgap and intermediate Auger recombination properties.

3 DEVICE CONCEPT

Figure 5 shows a possible hot carrier device concept. As well as the very specialised absorber properties, special contacts to the outside world are also required.

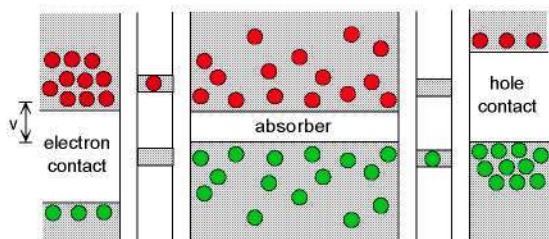


Figure 5: “n-i-p” hot carrier device concept.

In a normal low resistance contact, the net current flow is the small difference between carriers flowing in opposite directions. For a hot carrier absorber, the hot carrier flows from the absorber would be almost balanced by cold carrier flows from the contact, destroying the hot carrier effect. This problem can be avoided if current flow between the absorber and contact is restrained to a narrow range of energies.

Resonant tunneling through a single layer of quantum dots in a dielectric matrix is one way of achieving this narrow band transport (Fig. 6) [2]. An additional refinement shown in Fig. 5 is to use large bandgap, heavily doped semiconductors as the contact [5]. This not only closes off unwanted transport channels as suggested by Fig. 5, but also provides the “built-in” potential against which the photovoltage can operate.

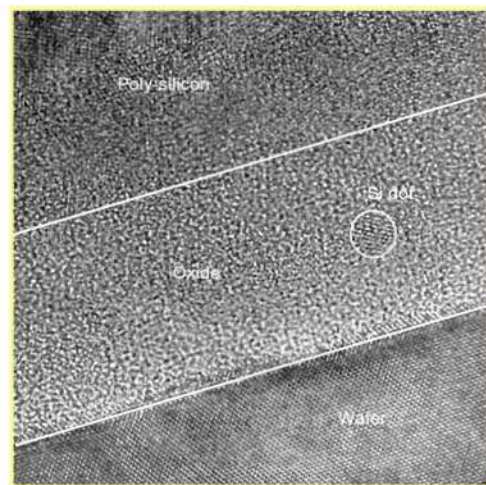


Figure 6: Resonant quantum-dot structure.

4 HOT PHONONS

A promising way of preventing the energy relaxation of photoexcited electrons may be to create a “hot” phonon population by making it difficult for optical phonons to decompose into acoustic phonons

By way of example, Fig. 7 shows the energy-crystal momentum relationship and phonon density of states (DOS) calculated for InN [6]. A clear phononic bandgap exists between the low energy acoustic phonons and the high energy optical phonons.

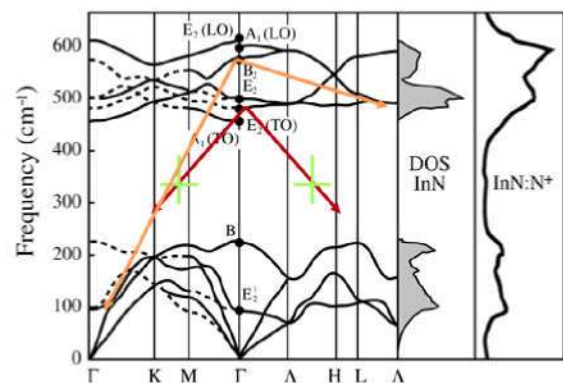


Figure 7: Phononic properties of InN [6].

For the highest energy acoustic phonons, the light N atoms are stationary and the heavy In atoms oscillate against them with the associated energy proportional to the inverse of the In atom mass. Conversely, for the lowest energy optical phonons, the In atoms are stationary and the light N atoms vibrate against them. The difference between the two associated energies explains the gap. Moreover, since In atoms are more than 4 times heavier than N atoms, the gap is larger than the highest energy in the acoustic band.

The way a photoexcited carrier normally relaxes to the band edge is by emitting high energy optical phonons. These have relatively low group velocity (determined by flatness of bands) and so are relatively immobile. However, an optical phonon can normally decay into 2 acoustic phonons in an energy and momentum conserving process (Klemens process). Acoustic phonons are relatively mobile and can carry off the energy. However, in InN, the Klemens mechanism is not possible since the optical phonon energy is more than twice that of any acoustic phonon. It must decay into at least 3 acoustic phonons, suppressing delay rates, with some experimental evidence for this available [7].

This gives rise to real prospects for the optical phonons population to be higher than in thermal equilibrium (ie. To become hot). The situation is analogous to that of a semiconductor with its 2 bands when electrons are photoexcited. Having hot phonons in turn slows the rate of electrons can impart energy to the optical phonons, slowing their cooling.

Although InN has a near-ideal bandgap for a hot-carrier cell, In is a scarce element thereby making the material unattractive as a third-generation option. Other light-heavy combinations may be more interesting. Alternatively, similar phononic bandgaps may be able to be created in nano-engineered materials.

5 POSSIBLE DEVICE IMPLEMENTATION

Based on the above discussion, a possible hot carrier cell concept is shown in Fig. 8. An n-type transparent conducting oxide is used as the top contact, with a heavily doped p-type contact at the rear (transparency might be an advantage in light-trapping). Small, high resonant energy state quantum dots are used to provide resonant electron and hole transport between the absorber and the respective contacts. The absorber itself is made of larger, uniformly spaced, core-shell quantum dots. Our studies suggest that having three mechanical properties to work with, namely the stiffness of the core, of the shell and of the matrix material, provides the flexibility required to engineer the desired phononic gaps.

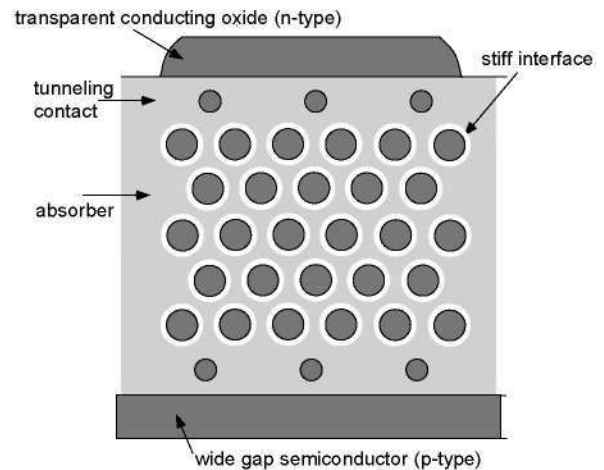


Figure 8: Conceptual hot carrier cell based on nano-engineered phononic properties.

6 CONCLUSIONS

If limits are accepted on the number of tandem cells that can be stacked, hot carrier cells become arguably the highest efficiency photovoltaic concept yet suggested. Unusual monoenergetic contacts and special absorber properties are required. The selective energy contacts appear achievable using resonant tunneling transport. Phononic engineering appears the best option for slowing carrier cooling in the absorber. New ideas in this area are still needed.

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