SOLAR ENERGY

GCEP

Global Climate & Energy Project
STANFORD UNIVERSITY

Hot Carrier Solar Cell: Implementation of the Ultimate Photovoltaic Converter

Investigators

Gavin Conibeer, Martin A. Green, University of New South Wales, Sydney; Antonio Marti and Antonio Luque, Instituto de Energia Solar, Madrid

Objective

This research aims to develop, for the first time, a proof-of-concept device of a hot carrier solar cell using abundant and non-toxic materials, and having a design compatible with thin-film deposition processes. Hot carrier solar cells have the prospect to achieve extremely high light-to-electricity energy conversion efficiency and have a structure that is conceptually simple compared to other very high efficiency devices such as multijunction monolithic tandem cells. They represent one of the most promising photovoltaic concepts to dramatically reduce the cost of solar energy.

Background

The hot carrier solar cell concept belongs to the so-called “third generation” solar cell technologies that investigate photovoltaic conversion schemes with the potential to reach efficiencies substantially higher than the theoretical efficiency limit for traditional single-junction devices (31%). In this scheme, solar-to-electricity energy conversion is enhanced by reducing energy losses related to the absorption of solar photons with energy larger than the bandgap E_{BG} of the active photovoltaic material. Subsequent to the absorption of a photon with energy $E_{ph}>E_{BG}$, an electron of the valence band is promoted to an excited state in the conduction band that naturally decays to the bottom of the conduction energy band on a timescale of tens of picoseconds.

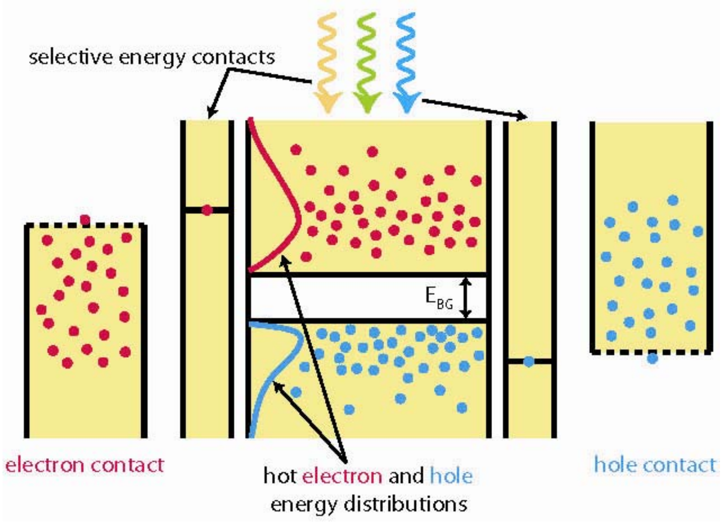

Figure 1: Band diagram of a hot carrier solar cell. Energy distributions of hot electron and hole populations created by photon absorption are shown together with selective energy contacts and cell electrodes.

This relaxation process is accompanied by the conversion of the excess energy (~E_{ph}-E_{BG}) into thermal energy. In other words, non-equilibrium "hot" carrier populations created by photon absorption, as illustrated in Figure 1, "cool down" and transmit their energy surplus to the semiconductor material lattice in the form of vibration modes – called phonons. This energy is lost for electricity production. Multijunction devices and other multiple energy-level approaches such as intermediate band solar cells, address this thermodynamic loss mechanism by having distinct structures within the cell absorb different portions of the solar spectrum, thus minimizing E_{ph}-E_{BG}. Such systems can reach very high conversion efficiency but often at the price of increasing the complexity of the architecture and consequent elevated production costs. The hot carrier concept adopts a fundamentally different strategy: hot electrons in the conduction band are extracted before they thermalize, resulting in increased photovoltage at the cell electrodes and theoretical light-to-electricity conversion efficiency limits as high as 68% under one-sun illumination conditions.

Approach

The challenges to realizing such hot carrier solar cell devices fall into two categories:

(1) Thermalization mechanisms must be retarded relative to radiative recombination rates. The major carrier cooling mechanism is the interaction with phonons in the semiconductor lattice. On a very short timescale (picoseconds) hot carriers relax by the emission of optical phonons. Subsequent cooling to the band edge occurs via acoustic phonon scattering (Klemens mechanism, illustrated in Figure 2). Therefore, approaches that interfere with optical to acoustic phonon scattering have the potential to significantly reduce carrier cooling rates. It has been shown that periodic networks of quantum structures, such as semiconductor nanoparticles, incorporated into the absorber material can significantly reduce the scattering between phonon modes. This effect – called the "phonon bottleneck" – will be implemented in this project by engineering a nanoparticle network embedded in an absorber matrix that is homogeneous on a scale greater than a few tens of nanometers. Such a structure is compatible with thin-film deposition techniques and retains the potential for high efficiencies.

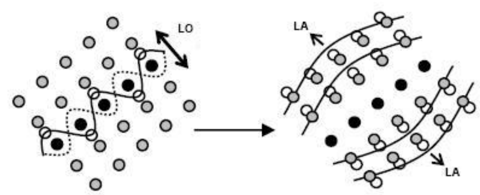

Figure 2: Schematic representation of the Klemens mechanism describing the decay of one optical phonon (LO) into 2 acoustic phonons (LA)

(2) Selective energy contacts must be developed that are able to extract charges through a narrow allowed energy range so as to prevent cold carriers in the contacts cooling the hot carriers to be extracted. Quantum mechanical resonant tunneling structures are the most likely to satisfy the requirements of selective energy transmission over a small energy range. In this project, these structures take the form of double barrier resonant tunnel structures with the resonant energy level provided by a single quantum dot layer whose size, uniformity, and density will be optimized against overall cell performance.

Initial structures for the absorber layer with periodic quantum dot arrays and for the selective energy contacts will be modeled, characterized, and eventually integrated into a combined device. First device prototypes will use III-V semiconductors grown with metal-organic vapor phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) techniques. After demonstration of the successful operation of these prototypes, the project will focus on investigating strategies to transfer such devices to thin-film or self-assembly deposition technologies using abundant and non-toxic group IV materials such as silicon and tin. Time resolved spectroscopy will be used throughout the project. The first phase will serve to establish an effective structure. Subsequently, thin-film structures fabricated from low-cost materials will be tested to learn if they can sustain a hot carrier population.