Nano/Energy Journal Club

Hot Carrier Solar Cell: Bringing it Back to Reality

Led by: Kyle Montgomery

01/29/2010

Hot Carrier Solar Cell (HCSC) First Paper

- Paper: **Y. Takeda, et al., "Hot carrier solar cells operating under practical conditions,"** ***Journal of Applied Physics*****, vol. 105, pp. 074905-10, 2009.**
- Paper received: July 14, 2009
- Toyota Central R&D Labs, with the PV Center at UNSW

Hot Carrier Solar Cell (HCSC) Second Paper

- Paper: **K. Kempa, et al., "Hot electron effect in nanoscopically thin photovoltaic junctions,"** ***Applied Physics Letters*****, vol. 95, pp. 233121-3, 2009.**
- Paper received: October 19, 2009
- Department of Physics, Boston College

HCSC: The basics

- Standard solar cell configuration:
  - Photons w/energy > bandgap are absorbed
  - Photons w/energy < bandgap are transmitted
- Name of the Game: Collection of generated electrons with energy > bandgap ***before*** they thermalize down to the bandedge
- Could allow for V_{oc} larger than E_G/q
- **Problem**: Thermalization happens on the femto-second time scale

Quasi-Band Diagram

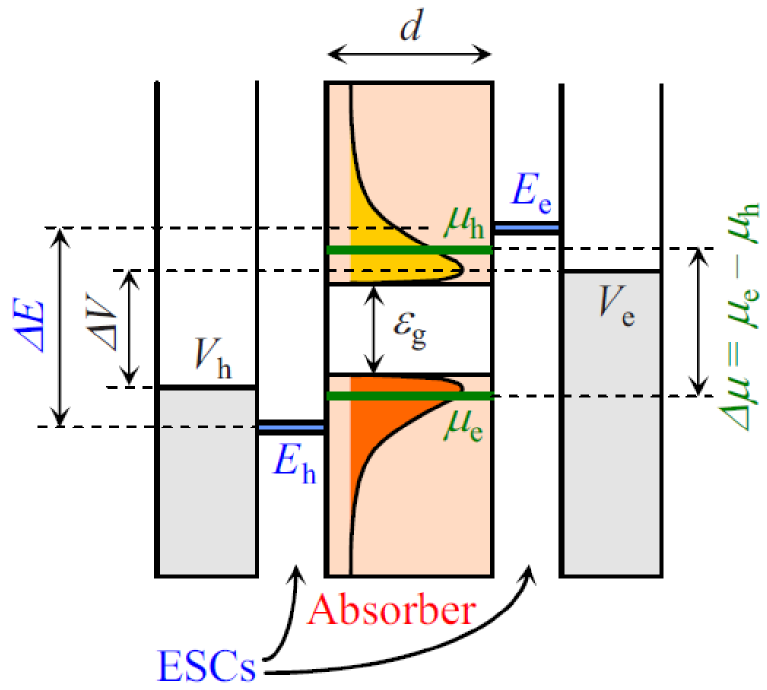
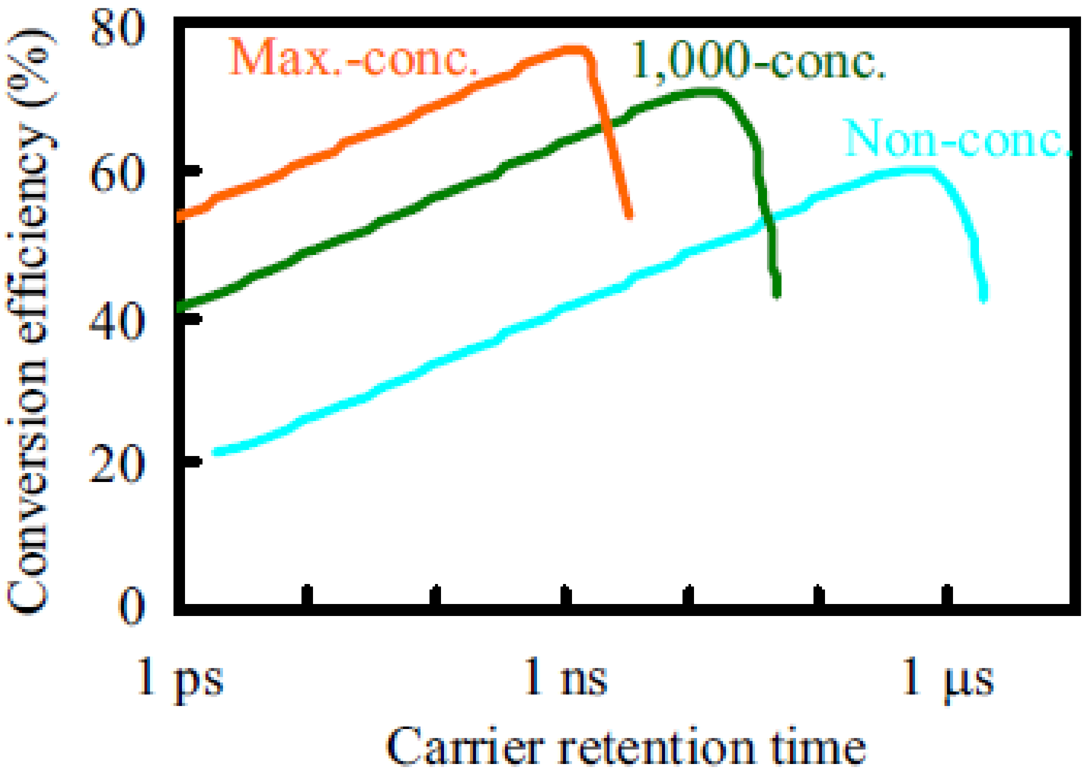


FIG. 1. (Color online) Configuration and energy diagram of a HC-SC. ε_g: bandgap of the absorber. d: thickness of the absorber. μ_e, μ_h: quasi-Fermi levels in the absorber. E_e, E_h: energy levels of the ESCs. V_e, V_h: Fermi levels in the metal electrodes. The suffixes e and h denote electrons and holes, respectively.

Ideal Case

- Max Efficiency: 85%
  - Assuming: max concentration, no thermalization, 100% absorption of solar photons with $h\nu > E_G$
- Takeda's "Practical" Limit: 50-55%
  - Assuming: thermalization time of 1ns, 1000x concentration, 100% absorption of solar photons with $h\nu > E_G$

Effect of Retention Time



- ~40% efficient without concentration
- ↑ Conc, ↑ Carrier concentration
- Drop off due to exponential increase in outgoing energy flux by emission

Problem # 1: Thermalization

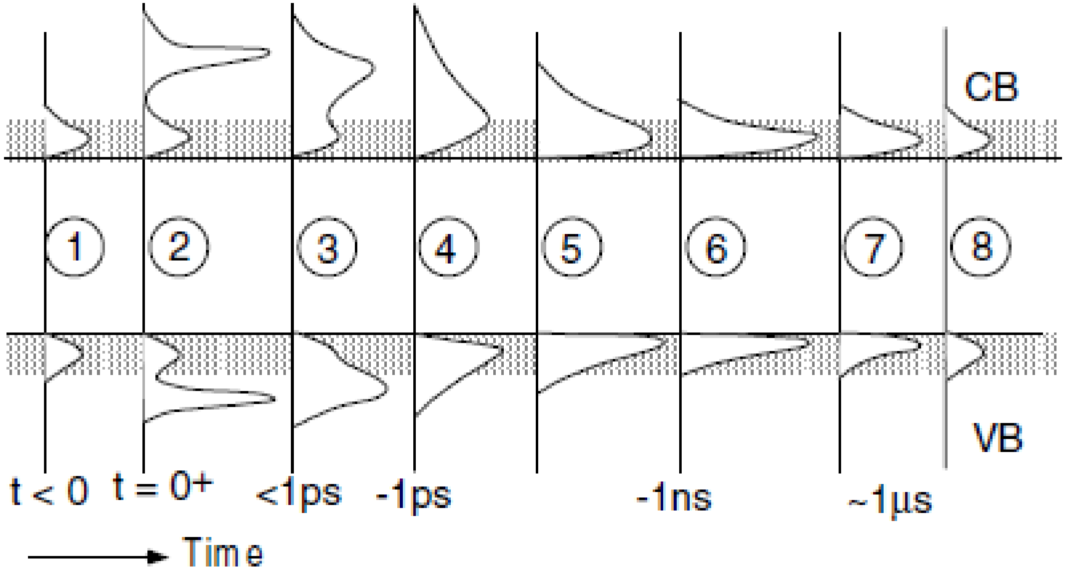


Fig. 6.2: Time evolution of electron and hole distributions in a semiconductor subject to a short, high intensity, monochromatic pulse of light from a laser: (1) Thermal equilibrium before pulse; (2) "coherent" stage straight after pulse; (3) carrier scattering; (4) thermalisation of "hot carriers"; (5) carrier cooling; (6) lattice thermalised carriers; (7) recombination of carriers; (8) return to thermal equilibrium.

Limits collection distance to ~ 10nm

M. A. Green, *Third Generation Photovoltaics*: Springer, 2003, p. 70.

Problem # 1: Thermalization (cont.)

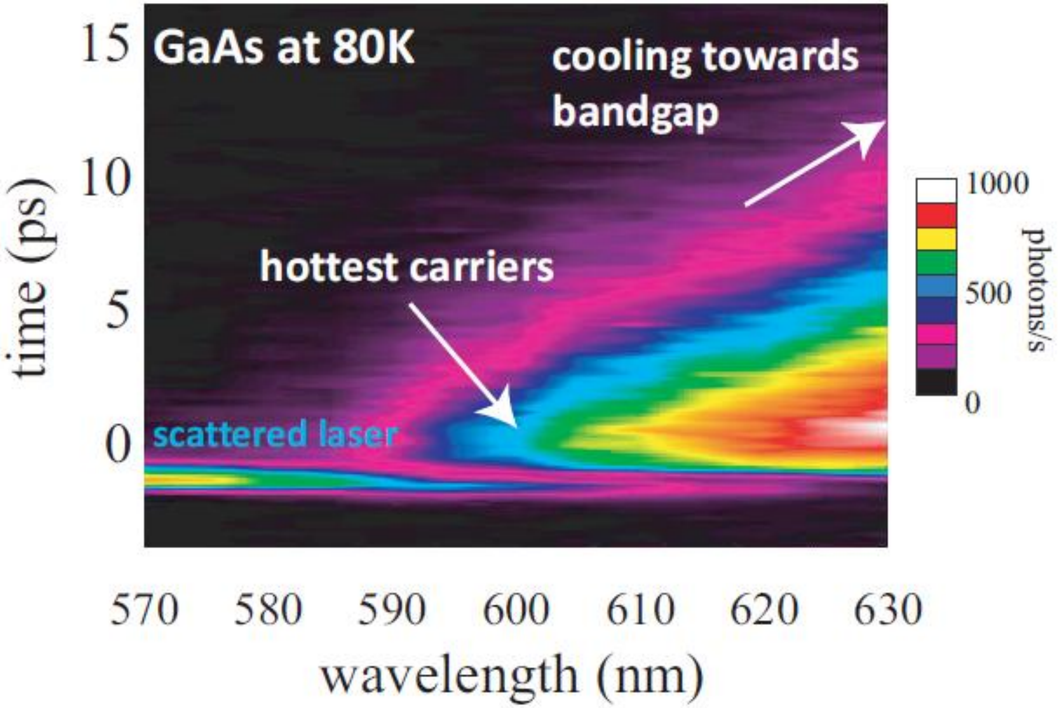


Figure 3: A portion of the TRPL of GaAs at 80K after illumination with a 150fs, 460nm laser pulse. The hottest carriers are very short-lived, on the order of a few picoseconds.

From the University of Sydney

T. W. Schmidt et. al., *Hot Carrier Solar Cell: Implementation of the Ultimate Photovoltaic Converter, Annual Report April 2009*, 2009, p. 23.

Problem # 2: Absorption

- Absorber Thickness (d) $\propto$ Thermalization Time Constant (τ_{th})
- With $\tau_{th} = 1$ps, thermalization distance $\approx$ 10nm (per M. Green)
- Oops! Typical bulk direct gap materials (α = 10^5/cm) need ~ 500nm to absorb 99% of solar photons
- Stuck with collecting a fraction of the photons

Problem # 3: Contacts

- Is it possible to extract HOT carriers into COLD carriers without losing the excess energy?
  - Maybe so…assuming carriers cool isentropically when going from T_H to T_A
  - Confused yet? I am!

Problem # 3: Contacts (cont.)

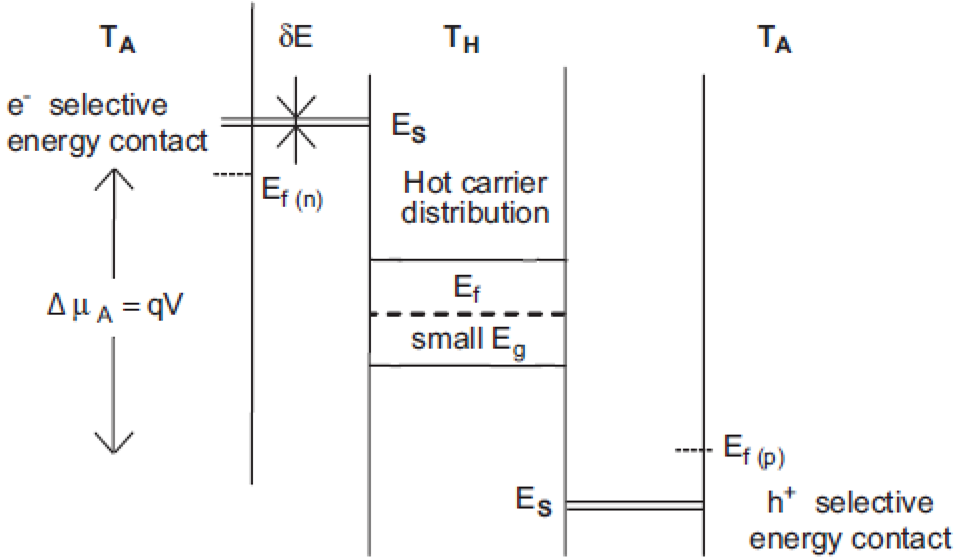
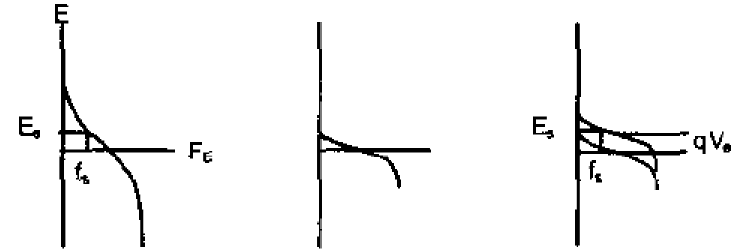


Fig. 1. Band diagram of an ideal hot carrier solar cell. The absorber has a hot carrier distribution at temp T_H. Carriers cool isoentropically in the mono-energetic contacts to T_A. The difference of the Fermi levels of these two contacts is manifested as a difference in chemical potential of the carriers at each contact and hence an external voltage, *V*.



a.) Hot carrier distribution at T_H

b.) Ambient carrier distribution at T_A

c.) At T_A with a mono-energetic contact

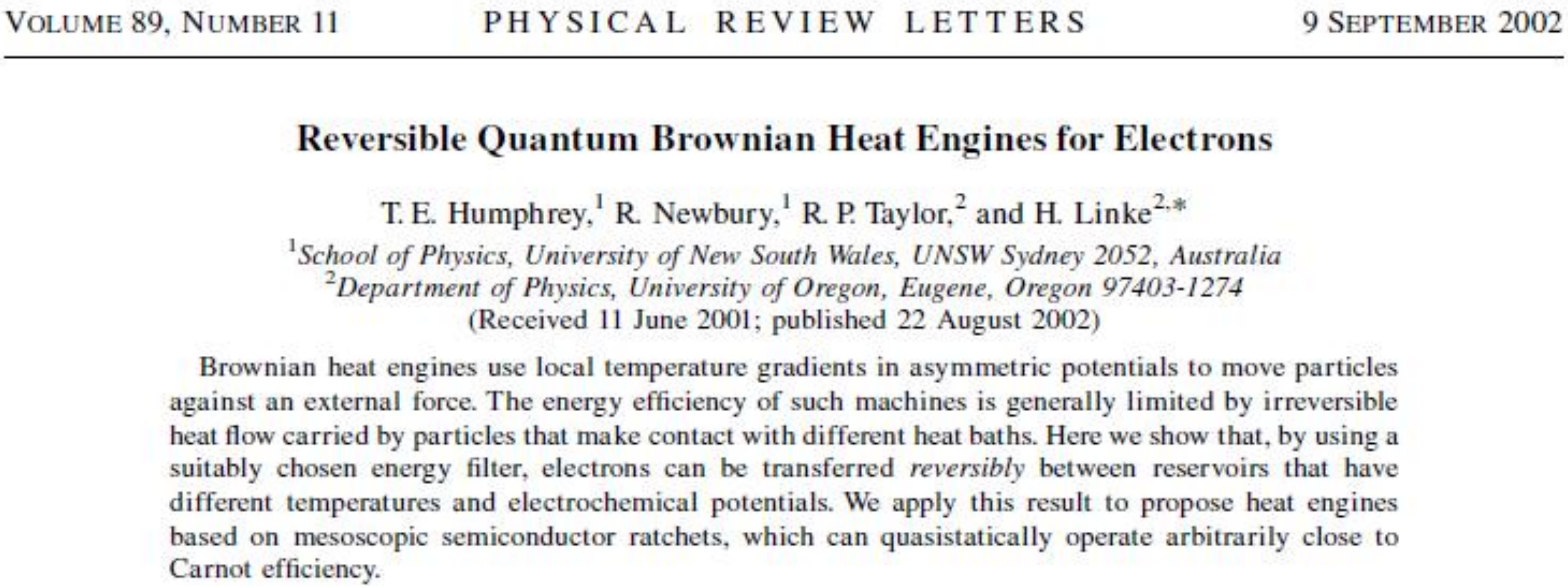
ig. 3 Fermi distributions at T_H (a) and T_A (b) for electrons. The generated voltage, V_e, in (c) is that required to match the distribution function, f_s, for the selected energy, E_s, at T_A with that at T_H, as would be the case in mono-energetic contacts. [8] (The hole contact is similar, generating V_h, and $V= V_e + V_h$.)

G. Conibeer, et al., "Selective energy contacts for potential application to hot carrier PV cells," in *Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on*, 2003, pp. 2730-2733 Vol.3.

G. Conibeer, et al., "Progress on hot carrier cells," *Solar Energy Materials and Solar Cells*, vol. 93, pp. 713-719, 2009.

Problem # 3: Contacts (cont.)

For more details on how this works, see:



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Reversible Quantum Brownian Heat Engines for Electrons

T. E. Humphrey,[1] R. Newbury,[1] R. P. Taylor,[2] and H. Linke[2,*]
[1]*School of Physics, University of New South Wales, UNSW Sydney 2052, Australia*
[2]*Department of Physics, University of Oregon, Eugene, Oregon 97403-1274*

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Brownian heat engines use local temperature gradients in asymmetric potentials to move particles against an external force. The energy efficiency of such machines is generally limited by irreversible heat flow carried by particles that make contact with different heat baths. Here we show that, by using a suitably chosen energy filter, electrons can be transferred *reversibly* between reservoirs that have different temperatures and electrochemical potentials. We apply this result to propose heat engines based on mesoscopic semiconductor ratchets, which can quasistatically operate arbitrarily close to Carnot efficiency.

Problem # 3: Contacts (cont.)

- However, this process relies on a key point:
  - Width of energy bands must be infinitesimally thin (up to 10meV may be OK)
  - If not, then entropy will be generated (carriers will lose energy through phonon interaction)
  - Thus the selectivity of an energy "filter" must be significant

Slowing Thermalization

- GOAL: Disrupt the Klemens Mechanism (decay of optical phonon into 2 longitudinal acoustic phonons)
  - Would keep the hot optical phonon population intact, which provides heat to carrier population

G. Conibeer, et al., "Progress on hot carrier cells," *Solar Energy Materials and Solar Cells*, vol. 93, pp. 713-719, 2009.

Slowing Thermalization (cont.)

- Use the “phononic band gap” (highest acoustic phonon energy to lowest optical phonon energy)
  - Material possibilities: InN, BiN, SnO
- Low-D phononic structures
  - Engineer mini-gaps in superlattices of QWs or QDs to prevent optical phonon decay and enhance phonon bottleneck effect
- These, among other ideas, still mostly in theoretical / modeling stages

G. Conibeer, et al., "Progress on hot carrier cells," *Solar Energy Materials and Solar Cells*, vol. 93, pp. 713-719, 2009.

Contacts: Example

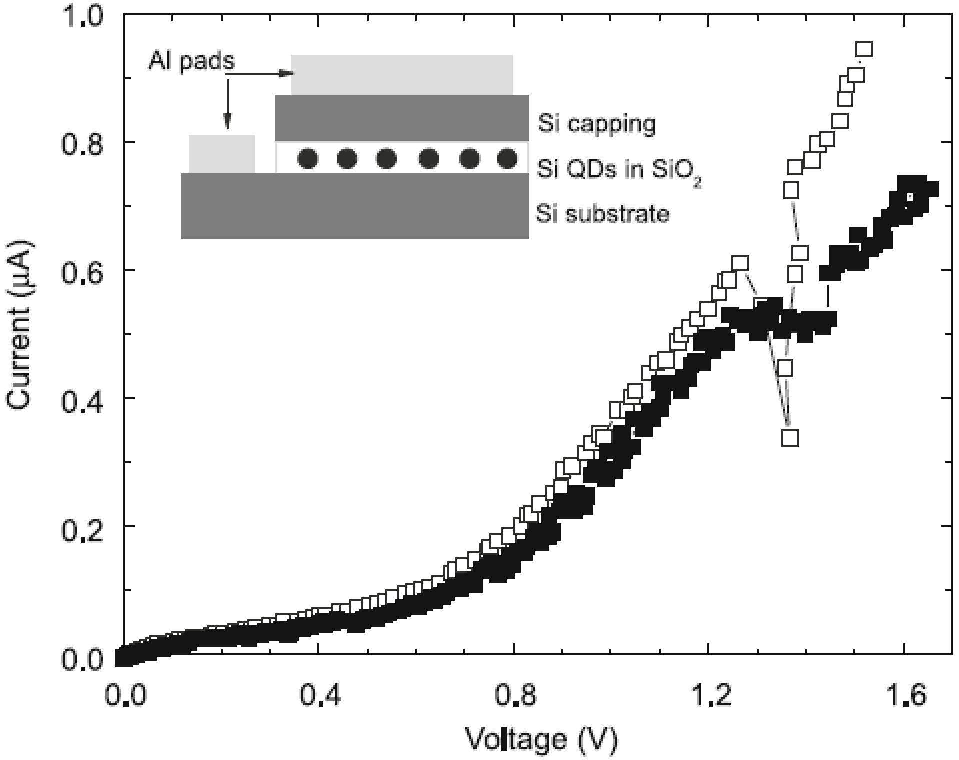


Fig. 5. Results of two consecutive *I*–*V* measurements at room temperature on a typical resonant tunnelling device are shown. The open and filled data points represent the first and the second measurements, respectively. Structure of the device is schematically shown in the inset.

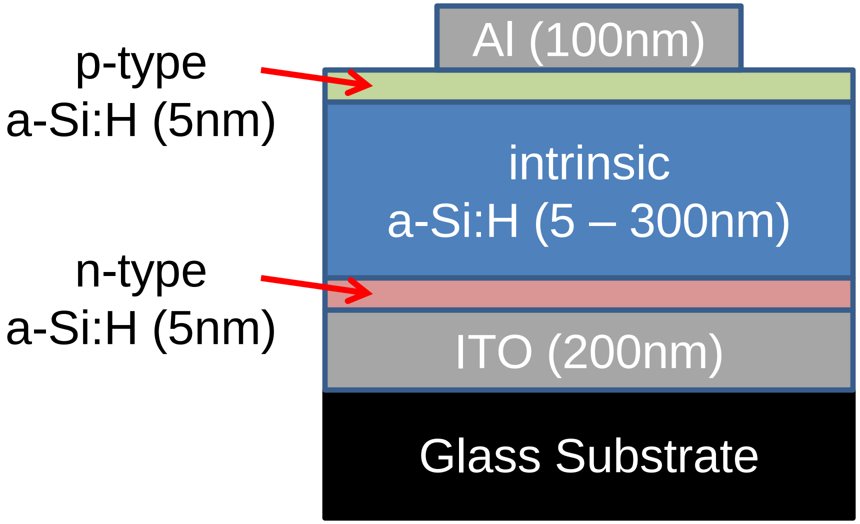
- QDs preferred over QWs due to confinement in extra dimension
- Broad half-width NDR peak: 400meV
- Likely due to varying sizes of QDs

S. K. Shrestha, et al., "Energy selective contacts for hot carrier solar cells," *Solar Energy Materials and Solar Cells*, vol. In Press, Corrected Proof, 2010.

Case Study:

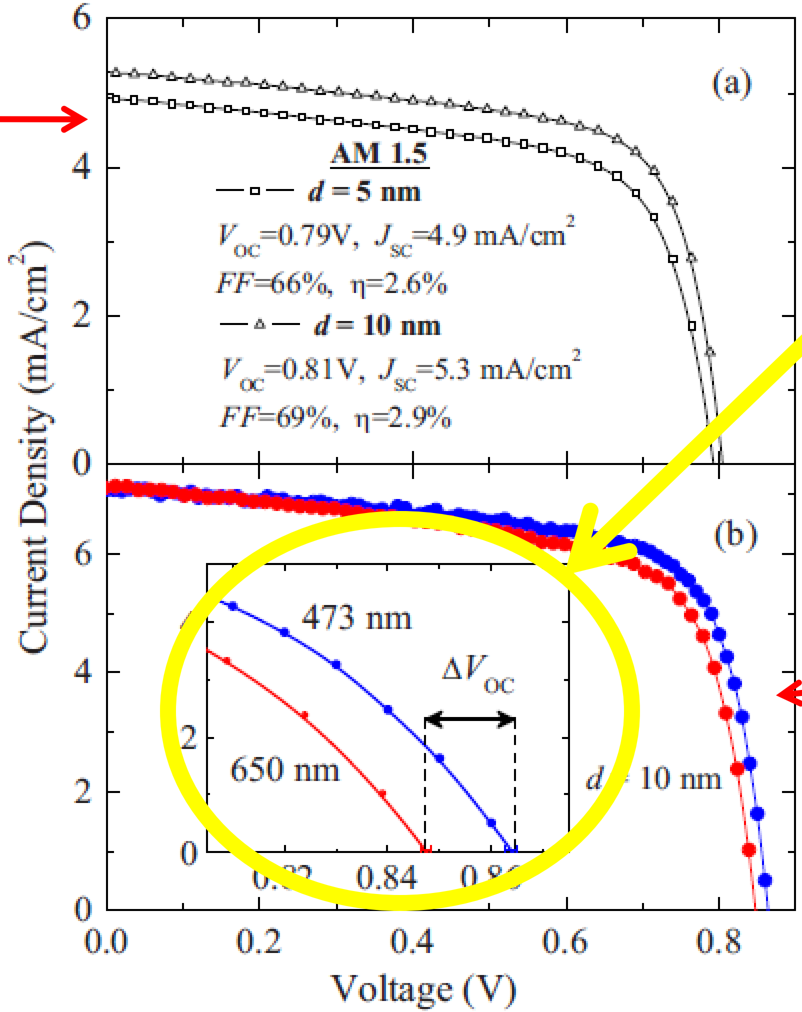
The Boston College Approach

- Standard a-Si:H configuration (grown by PECVD), with a variable i-layer thickness
- i-layer thickness denoted by “***d***” in figures



I-V Characteristics

AM1.5



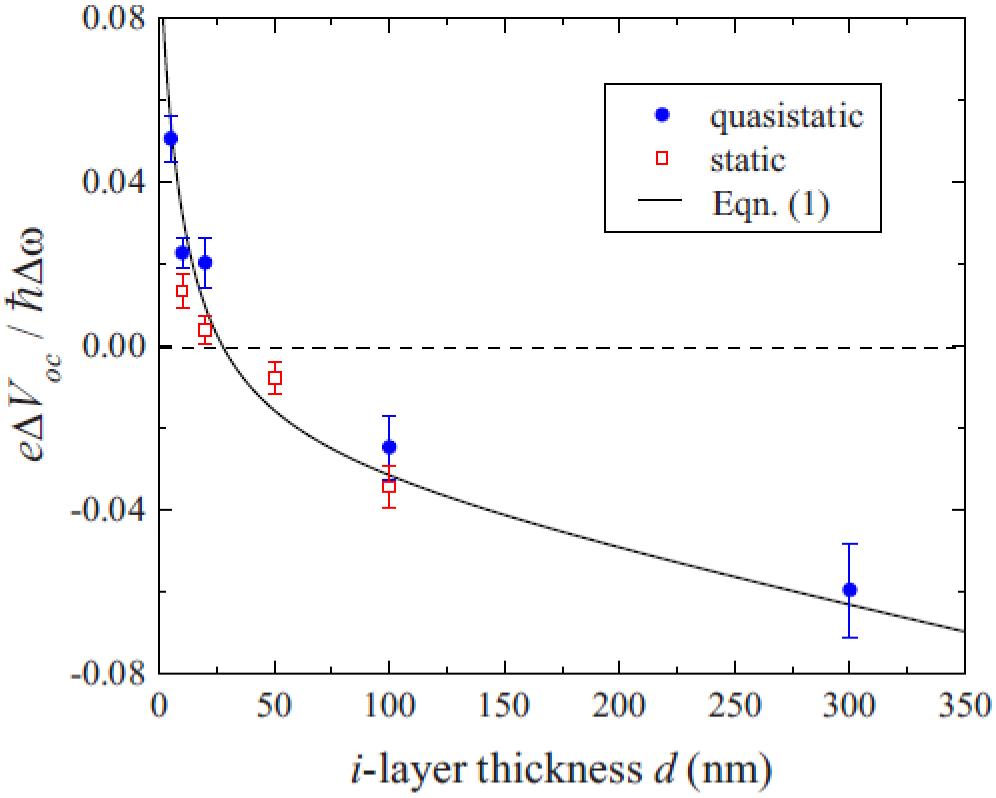
Key finding shown here: larger Voc for higher energy photons

Monochromatic laser illumination

(laser intensity adjusted to get same Jsc)

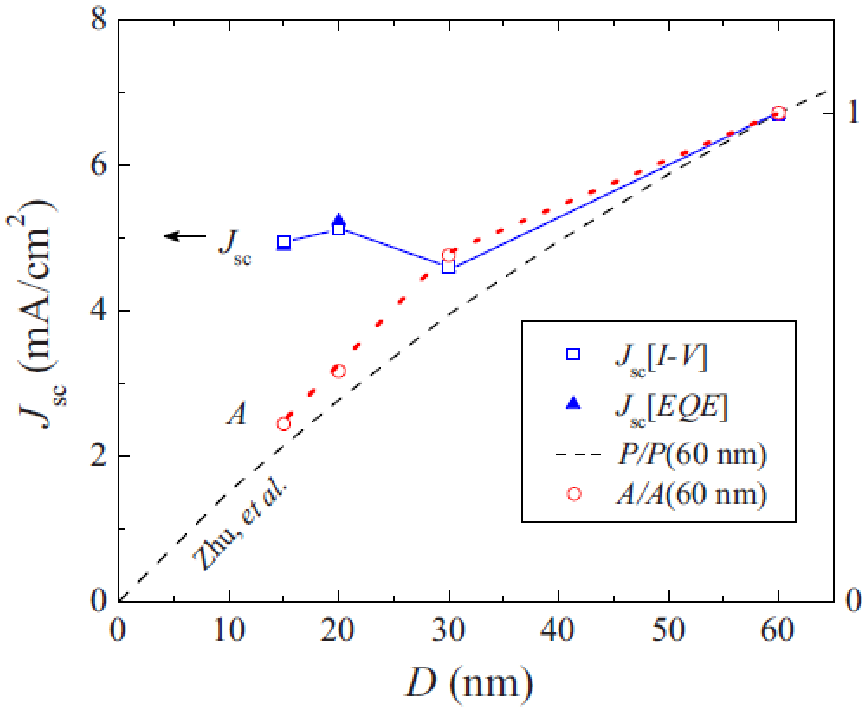
Function of i-layer Thickness

- ΔVoc is:
  - *positive* for ultrathin junctions
  - *decreases* monotonically with thickness
  - becomes *negative* for d>30nm
- Solid line represents a curve following a derived phenomenological form



Field-Assisted Collection

- Expectation is that Jsc decreases continuously as thickness decreases (shown by dashed lines)
- Results show increase in Jsc for ultrathin cells due to high junction electric field (~10^8 V/m)
- Jsc of 5mA is about ½ that of typical a-Si cells of 400nm thickness



Hot Electron Effect? Not Really…

- Standard cell/contact configuration means any extracted “hot” carriers will thermalize down to the Fermi level in the contacts immediately
- Increase in V_{oc} with blue laser possibly due to reduction of I_0 (remember: $V_{oc} \propto \ln(I_L/I_0)$)
  - Higher thermal energy allows for ballistic transport through depletion layer (i.e. less recombination)
- No mention of Staebler-Wronski effect (UV degradation, well-known) or other a-Si measurement issues

Concluding Remarks

- Do the pieces make sense?
  - I would say YES.
- Is it possible to fit all the pieces together, and come out with a high efficiency cell?
  - Perhaps, but the execution will be far from a trivial exercise.
  - Not to mention that you have to compare this with the difficulty in making a silicon p-n junction (or at least a 3 or 4 junction tandem cell).