**Nanotechnology for more efficient photovoltaics: the quantum dot intermediate band solar cell**

**Antonio Luque**
Instituto de Energía Solar, Universidad Politécnica de Madrid, 28040 Madrid, Spain
a.luque@upm.es

The intermediate band solar cell[1] has been proposed as a concept able to substantially enhance the efficiency limit of an ordinary single junction solar cell. If a band permitted for electrons is inserted within the forbidden band of a semiconductor then a novel path for photo generation is open: electron hole pairs may be formed by the successive absorption of two sub bandgap photons using the intermediate band (IB) as a stepping stone. While the increase of the photovoltaic (PV) current is not a big achievement —it suffices to reduce the bandgap— the achievement of this extra current at high voltage is the key of the IB concept. In ordinary cells the voltage is limited by the bandgap so that reducing it would also reduce the bandgap. In the intermediate band solar cell the high voltage is produced when the IB is permitted to have a Quasi Fermi Level (QFL) different from those of the Conduction Band (CB) and the Valence Band (VB). For it the cell must be properly isolated from the external contacts, which is achieved by putting the IB material between two n- and p-type ordinary semiconductors[2]. Efficiency thermodynamic limit of 63% is obtained for the IB solar cell[1] vs. the 40% obtained[3] for ordinary single junction solar cells. Detailed information about the IB solar cells can be found elsewhere[4].

IB solar cells may be implemented by nanotechnology[5]. In particular the IB can be formed by the bound states of quantum dots of a lower gap semiconductor located inside a wider bandgap host semiconductor. The first practical realization was made with InAs QDs in a GaAs matrix[6]. Other groups have prepared similar devices[7-11]. Highest efficiency so far has been 18%[10]. In reality present QD IB solar cells present a negligible increase of the photocurrent and a substantial reduction of the voltage so that they always present less efficiency than test structures of the same host semiconductor without QDs.

As matter of fact one of the reasons of this reduced efficiency is that the InAs/GaAs system is very inappropriate. The increased thermodynamic efficiency limit is achieved for a bandgap of about 2 eV and a position of the IB band at 0.7 e.V from the CB whereas in the InAs/GaAs system has a total bandgap of 1.42 eV at room temperature and the position of the IB is at about 0.25-0.30 eV form the GaAs CB. Calculations[12] show that for these bandgaps the one-sun efficiency (the one referred to in all the cited publications) cannot exceed that of the cell without IB although the case might be different under concentrated sunlight. However, this materials system has permitted to experimentally prove the operational principles of this concept, namely the two photon mechanism[13] and the three QFL splitting[14] and its direct consequence, the achievement of voltage very close to the GaAs badgap[15]. Unfortunately this has only been possible to detect[13] or achieve[15] at very low temperature when the thermal escape has been suppressed.

The reduction of voltage of present QD IB solar cells is partly due to the reduction of minority carrier lifetime introduced through the dislocations created by the stresses. This has been amended by stress reduction of spacer increase and is not a major problem today. In part it is also due to the reduction of the bandgap due to the invasion of the bandgap by the heavy hole states[12,16] that form a quasi continuous, and by the formation of a wetting later that acts as a quantum well[12]. According to this, it is unfair use single gap cell without QDs with the cell with QDs in the same host material. Changing the bandgap of the host material this problem is solved. Yet the increase of current is very small and this is due by an inherent low absorption of the QDs for interband transitions. We think that the CB wavefunctions have an envelope with S symmetry[16] while this symmetry is absent in the VB wavefunctions. The consequence is that the relevant envelope wavefunctions overlap poorly. We don't know yet the solution to this issue, besides, of course, a photon management strategy to enhance the absorption.

Finally another issue is the thermal escape. It prevents form an easy splitting of the CB and IB QFLs. Best solutions are the reduction of the QD size to prevent QD excited states that may provide a ladder for the escape of electrons[17] and, of course, to change the material system to better exploit the potentialities of the concept[18].

**References**


[1] A. Luque and A. Martí, Physical Review Letters **78,** 5014–5017 (1997).
[2] A. Luque and A. Martí, Progress in Photovoltaics: Res. Appl. **9,** 73–86 (2001).
[3] W. Shockley and H. J. Queisser, Journal of Applied Physics **32,** 510-519 (1961).
[4] A. Luque and A. Marti, Advanced Materials **22,** 160-174 (2009).
[5] A. Martí, L. Cuadra, and A. Luque, in Proc. 28th IEEE Photovoltaics Specialists Conference (IEEE, New York, 2000), p. 940-943.
[6] A. Luque, A. Martí, C. Stanley, N. López, L. Cuadra, D. Zhou, and A. Mc-Kee, Journal of Applied Physics **96,** 903–909 (2004).
[7] S. M. Hubbard, C. D. Cress, C. G. Bailey, R. P. Raffaelle, S. G. Bailey, and D. M. Wilt, Applied Physics Letters **92,** 123512 (2008).
[8] V. Popescu, G. Bester, M. C. Hanna, A. G. Norman, and A. Zunger, Physical Review B **78,** 205321 (2008).
[9] R. Oshima, A. Takata, and Y. Okada, Applied Physics Letters **93,** 083111 (2008).
[10] S. A. Blokhin, A. V. Sakharov, A. M. Nadtochy, A. S. Pauysov, M. V. Maximov, N. N. Ledentsov, A. R. Kovsh, S. S. Mikhrin, V. M. Lantratov, S. A. Mintairov, N. A. Kaluzhniy, and M. Z. Shvarts, Semiconductors **43,** 514–518 (2009).
[11] D. Alonso-Alvarez, A. G. Taboada, J. M. Ripalda, B. Alen, Y. Gonzalez, L. Gonzalez, J. M. Garcia, F. Briones, A. Marti, A. Luque, A. M. Sanchez, and S. I. Molina, Applied Physics Letters **93,** 123114 (2008).
[12] A. Marti, E. Antolin, E. Canovas, N. Lopez, P. G. Linares, A. Luque, C. R. Stanley, and C. D. Farmer, Thin Solid Films **516,** 6716-6722 (2008).
[13] A. Marti, E. Antolin, C. R. Stanley, C. D. Farmer, N. Lopez, P. Diaz, E. Canovas, P. G. Linares, and A. Luque, Physical Review Letters **97,** 247701-4 (2006).
[14] A. Luque, A. Marti, N. Lopez, E. Antolin, E. Canovas, C. Stanley, C. Farmer, L. J. Caballero, L. Cuadra, and J. L. Balenzategui, Applied Physics Letters **87,** 083505-3 (2005).
[15] E. Antolín, A. Martí, P. G. Linares, I. Ramiro, E. Hernández, C. D. Farmer, C. R. Stanley, and A. Luque, in Proc.25 Photovoltaic Specialists Conference (IEEE, Honolulu, 2010).
[16] A. Luque, A. Marti, E. Antolín, P. G. Linares, I. Tobías, I. Ramiro, and E. Hernandez, Solar Energy Materials & Solar Cells**,** to be published (2011).
[17] A. Luque, A. Marti, E. Antolín, P. G. Linares, I. Tobias, and I. Ramiro**,** submitted (2011).
[18] P. G. Linares, A. Marti, E. Antolin, and A. Luque, Journal of Applied Physics **109,** 014313 (2011).