Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 8 (2011) 443–448

Energy
Procedia

SiliconPV: 17-20 April 2011, Freiburg, Germany

Cost model for LIMA device

M. A. Vázquez[a*], J. P. Connolly[b], O. Cubero[b], G. Daly[b], A. Halm[c], R. Kopecek[c], V. D. Mihailetchi[c], E. Pérez[b], G. Pucker[d], G. Sánchez[b], L. Pavesi[e]

[a]*ISOFOTON, S. A. Calle Severo Ochoa, 50, Malaga 29590, Spain*
[b]*Nanophotonic Technology Center – Universidad Politecnica de Valencia, Valencia 46022, Spain*
[c]*International Research Technology Center – ISC Konstanz, Rudolf-Diesel Str.15 , Konstanz D-78467, Germany*
[d]*Foundazione Bruno Kessler, Via Sommarive 18, Povo-Trento I-38050, Italy*
[e]*University of Trento, Via Sommarive, 14, I-38100 Trento, Italy*

Abstract

In this paper we show the results of the cost model developed in LIMA project (FP7-248909). The LIMA project is titled "Improve photovoltaic efficiency by applying novel effects at the limits of light to matter interaction". The project started in January 2010 and during this year a cost model of the device developed in the project has been developed to assess the industrial viability of this innovative approach to increase the efficiency and reduce the cost of photovoltaic solar cells. LIMA project exploits cutting edge photonic technologies to enhance silicon solar cell efficiencies with new concepts in nanostructured materials. It proposes nano-structured surface layers designed to increase light absorption in the solar cell while decreasing surface and interface recombination loss. Integration in a back contact design further reduces these interface losses and avoids shading. The project improves light-matter interaction by the use a surface plasmonic nanoparticle layer. This reduces reflection and efficiently couples incident radiation into the solar cell where it is trapped by internal reflection. Surface and interface recombination are minimized by using silicon quantum dot superlattices in a passivating matrix. The distance between quantum dots ensures wave-function overlap and good conductivity.

Keywords: Interdigitated back contact solar cells; silicon quantum dots; plasmonic layer; cost analysis.

---

* Corresponding author. Tel.: +34 951 23 3500; fax: +34 951 23 3211.
E-mail address: m.vazquez@isofoton.com .

1876–6102 © 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of SiliconPV 2011.
Open access under CC BY-NC-ND license. doi:10.1016/j.egypro.2011.06.163

1. Interdigitated back contact solar cell

The background device in LIMA project is an Interdigitated Back Contact (IBC) solar cell. This IBC solar cell will be used with novel layers on top. In the framework of this project IBC solar cells have been developed using industry standard compatible processes and CMOS compatible processes. The first process is a scalable process at industrial level based on screen-printing and laser technology, the second one a laboratory process based on photolithography processes. Naturally in the cost analysis and in this paper we focus on the first option. In turn, in the industrial process two options have been investigated: aluminum (Al) emitter and boron emitter IBC solar cells. Both technologies are based on n-type Cz-Si substrates and they are compatible with industrial processes like screen-printing, selective laser opening, diffusion in tube furnace and co-firing in belt furnace.

Al-based IBC solar cells imply that the emitter formation is formed by a screen printed Al paste, the subsequent alloying of Al with n-type silicon forms the p^+ emitter region. The base contact is formed by an Ag-based screen printing technique. The BSF and FSF are formed by diffusion of phosphorous in a tube furnace with $POCl_3$ flow. The selective laser opening is used for defining the n^+ and p^+ regions on the rear side of the wafer. The chemical processes used are the typical random pyramid texture (both sides), the single side polishing (rear side), the laser damage removal by alkaline etching and the PSG removal by acid etching before frontal deposition of silicon nitride.

The boron emitter IBC solar cell requires two diffusion steps. The BBr_3 is the precursor used for boron diffusion in tube furnaces. The rest of processes are similar. The design of the solar cell is shown in figure 1.

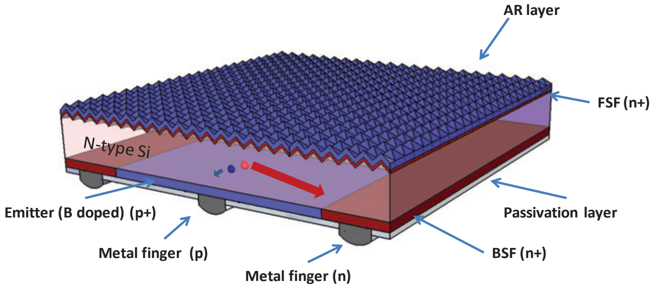


Fig. 1. Back contact cell design based on boron doped emitter.

The best solar cell result obtained during the first year of the LIMA project is shown in the figure 2. The electrical results are: efficiency 19.6%, V_{OC} 624mV, J_{SC} 41.4 mA/cm^2 and FF 75.7%.

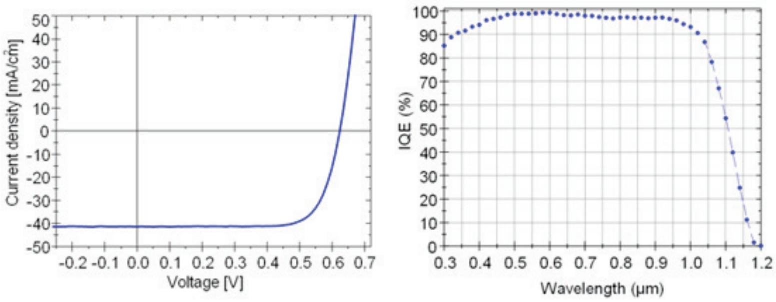
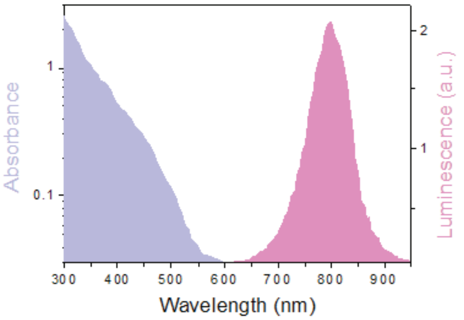


Fig. 2. Iluminated IV-curve and spectral response (IQE) of the best IBC solar cell with an efficiency of 19.6%.

2. Growth of silicon-nanocrystal

The project aims to integrate two additional layers on basic device that is IBC solar cell: a silicon quantum (Qd-Si) dots layer and a plasmonic layer. We plan to utilize silicon nanocrystals as optical downshifter or down converters. The nanocrystals consist of only a few hundred atoms. They effectively absorb the UV part of the sunlight and reemit it in the red part of the spectrum. This is helpful since UV radiation is not absorbed efficiently by standard solar cells, whereas the red part of the spectrum is very effectively converted into electrical energy. Thus, a shift in color will enhance the overall performance of the solar cell.

A new approach is investigated in this project for Qd-Si layer: the silicon-nanocrystals will be grown embedded in a passivated dielectric layer. This has two main advantages: unlike amorphous silicon, the Si-Qd layer does not suffer from long term stability issues[1], and there is evidence of multiple exciton generation for high energy incident photons [2] .



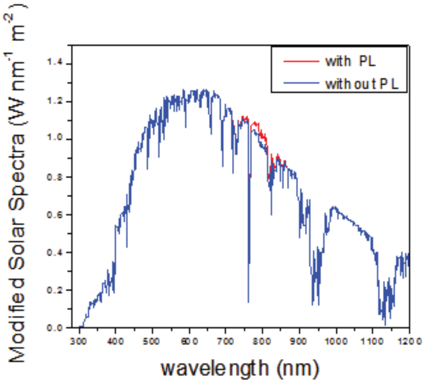


Fig. 4. (Left) The blue curve shows the absorption of the UV light and the purple curve shows the reemission in the red. First measurements indicate a conversion efficiency of 10-20% [2].

Fig. 5. (Right). The modulation of the solar spectrum caused by the downshifting effect has been modelled theoretically. The blue curve shows the light that get into the solar cell without the photoluminescence effect of the SiQd and the red one shows the gain in the red part of spectrum due the presence of the nanocrystal.

There exist a series of similar ways to grow silicon-nanocrystal embedded in silicon-dioxide. Most of them start from a silicon-rich-oxide (SRO) layer, which under thermal annealing undergoes phase separation into silicon and silicon-dioxide. At low temperatures silicon is present in amorphous clusters, while to obtain crystalline layers are required process temperatures up to 1200°C. The SRO layer deposition will be carried out in a PECVD equipment and the annealing process in a convective quartz tube furnace. The PECVD deposition is compatible with silicon nitride deposition and the thermal process is compatible with boron diffusion process, so the thermal budget of the process could be optimised.

3. Plasmonic layer

The second novel light-matter interaction exploited is in the field of plasmonics. This is a novel method for increasing light absorption [3],[4] by the use of scattering from photoexcited noble metal nanoparticles, an effect maximized at their surface plasmon resonance. Such sub-wavelength particles when tailored with adequate size and shape enhance light trapping in a solar cell [5]. This can be used to enhance the performance of the Si-Qd layer by increasing the light intensity, in particular at the plasmonic resonant frequency of the nanoparticles. Three fabrication techniques of layers of metal nanoparticles (MNPs) will be explore in LIMA project [6]. The electron beam lithography (EBL) defining regular arrays of particles with controlled geometry, NanoSphere Lithography (NSL) yielding regular arrays with some loss of accuracy and reproducibility and Nanoparticle Self-Aggregation (NSA) leading to complete random distribution of metal nanoparticles. This last technique will be taken into account for the cost analysis and the industrial feasibility study.

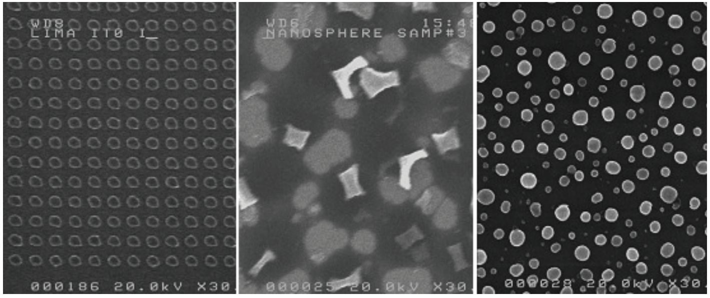
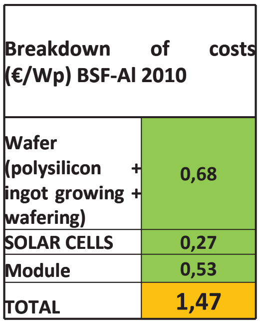


Fig. 6. Three methods of fabrication metallic nanoparticles EBL (left) with periodical and similar dimension, NSL (centre) preliminary test and NSA best result after process optimization.

4. Cost analysis and industrial viability

In 2008 was published [7] a cost assessment of standard technology based on mc-Si solar cells with 15% solar cell efficiency in the range of 2.13 €/Wp for module cost. In LIMA project a complete cost analysis study and industrial feasibility will be done. During the first year a preliminary cost analysis has been carried out to define the cost and the efficiency range to assure the successful of the technology at industrial scale. To build up the cost model have been considered a complete list of equipments and its features, energy consumption, personnel, materials and other details. The cost of standard technology based on p-type monocrystalline silicon solar cells and BSF-Al device have been estimated. The main assumptions have been: 50MW production line size that working with three shifts, substrate type: p-type monocrystalline silicon wafer, ten years for depreciation time of equipments, the electricity cost average is 0,084€/kWh [8]. The results have been a cost range between 1.62€/Wp and 1.32€/Wp for standard photovoltaic module, so an average rate of 1.47€/Wp can be consider as reference for solar cell efficiency of 17.5%. In three or four years the cost reduction has been above 30% from 2.13€/Wp until 1.47€/Wp.



Breakdown of costs (€/Wp) BSF-Al 2010	
Wafer (polysilicon + ingot growing + wafering)	**0,68**
SOLAR CELLS	**0,27**
Module	**0,53**
TOTAL	**1,47**

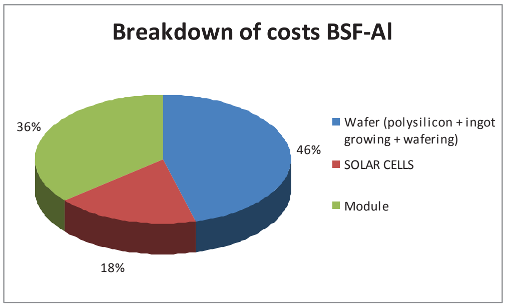


Fig. 7. Breakdown of module cost for BSF-Al technology.

In the following figure the cost estimation of solar module based on IBC solar cells and LIMA solar cells is showed. Additional equipments, energy, personnel, and materials have taken into account in the cost model. For LIMA technology has been considered that Qd-Si layer is formed by SRO deposition by PECVD reactor and thermal annealing in tube furnace, and the plasmonic layer is formed by silver deposition on the front side in PVD reactor and thermal annealing about around 300-500°C.

A solar cell efficiency threshold is found for IBC and LIMA technology to assure the industrial viability. This minimum efficiency would be 18.5% for IBC solar cell and 20.0% for LIMA solar cell with Si-Qd layer and plasmonic layer.

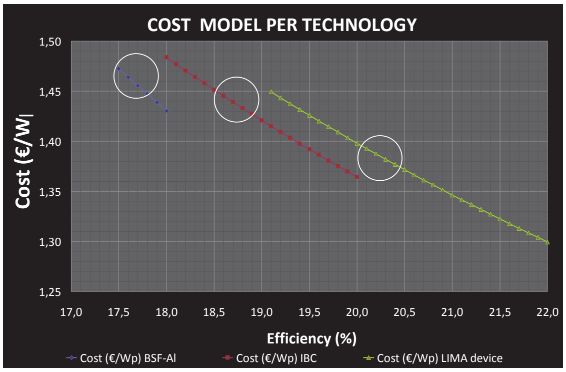
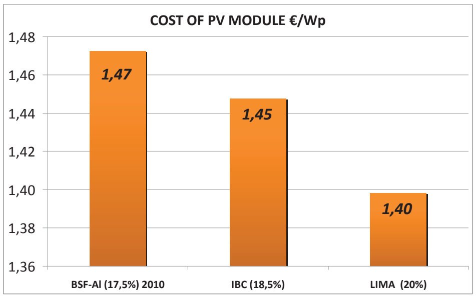


Fig.8. Module cost in €/Wp versus solar cell efficiency per technology. Threshold efficiency at solar cell level are shown for IBC technology (18.5%) and for LIMA technology (20%).

Once the cost model is built, we can compare the three technologies from the point of view of industrial viability. In the following figure we can compare the manufacturing cost, the return of investment (ROI) and the profit differential. The ROI is defined as the time (in years) is needed to balance the investment cost and the profits. The profit differential is referred to the profits of BSF-Al technology, so IBC technology shows 13.7% higher profits than BSF-Al technology and LIMA technology 36.7% higher than BSF-Al technology.



TECHNOLOGIES	MANUFACTURING COST (€/Wp)	ROI (years)	Profit Differential
BSF-Al	1,47	1,0	-
IBC	1,45	1,3	13,7%
LIMA	1,40	1,5	36,7%

Fig. 9. Comparison of the three technologies BSF-Al, IBC and LIMA. Manufacturing cost of PV module, return of investment (ROI) and profit differential are shown. The return of investment is defined as the time (in years) is needed to balance the investment cost and the profits.

5. Conclusions and future work

A novel third generation device based on IBC solar cells and two additional layers on top have been presented. The novel layers are a Qd-Si layer that works as optical down converter and a plasmonic layer for increasing light absorption.

The industrial viability of this photovoltaic device has been analyzed and the process flow of novel layers has been presented.

A cost model has been developed for IBC technology and advanced device based on IBC with Qd-Si layer and plasmonic layer.

The model shows this device will be industrially feasible if 20% efficiency is demonstrated at mass production solar cell level.

In this paper a 50MW production line scale has been analyzed. In the following two years the economical review and cost estimation at 500MW-1GW scale will be carried.

To reduce the investment cost a new scenario with a gel based method to deposit on large area the plasmonic layer will be analyzed.

Acknowledgements

This work has been carried out in the framework of the LIMA Project. The EC is gratefully acknowledged for financial support under Contract number FP7-248909.

References

[1] D. V. Talapin et al. “Highly Emissive Colloidal CdSe/CdS Heterostructures of Mixed Dimensionality” Nano Letters 2003 Vol. 3, No. 12 1677-1681.

[2] M. C. Hanna and A. J. Nozik, “Solar conversion efficiency of photovoltaic and photoelectrolysis cells with carrier multiplication absorbers” Journal of Applied Physics 100, 074510 (2006).

[3] T.V.Teperik, F. J. García de Abajo et al., Nature Photonics 2, 2008, pp. 229-301.

[4] V. E. Ferry et al. “Plasmonic Nanostructure Design for Efficient Light Coupling into Solar Cells”, Nano Lett., 2008, 8 (12), 4391-4397.

[5] T. Temple and D. Bagnall, “DDA Simulation of Gold Nanoparticles, With Applicability for Enhanced Absorption in Si Solar Cells”, Proc. 21st European Photovoltaic Specialists Conference, Dresden, September 2006 pp. 289.

[6] J. P. Connolly, et. al. “Analysis of plasmonic nanoparticle fabrication techniques for efficient integration in photovoltaic devices” Valencia 2010.

[7] C. del Cañizo, G. del Coso and W. C. Sinke, “Cristalline Silicon Solar Module Technology: Towards the 1 € Per Watt-Peak Goal”, Prog. Photovolt: Res. Appl. (2008).

[8] Source Eurostat. UE-15 industrial electricity price. Available from web page of “Ministerio de Industria, Turismo y Comercio” of Spain (www.mityc.es).