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Cost model developed in European project LIMA

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Abstract

In this paper we show the results of the cost model developed in LIMA project (Seventh Framework Programme, CN: 248909). The LIMA project is entitled “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. During 2011 the cost model has been actualized and a new scenario has been defined. The LIMA project exploits cutting edge photonic technologies to enhance silicon solar cell efficiencies with new concepts in nanostructured materials. It proposes nanostructured surface layers designed to increase the light absorption in the solar cell while decreasing the surface and interface recombination loss. The integration on a back contact solar cell 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.

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

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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 based on n-type Cz-Si substrates, boron emitter by diffusion in tube furnace, selective laser opening, screen-printing metallization and co-firing in belt furnace. 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.

2. Growth of silicon-nanocrystal and plasmonic layer

The project aims to integrate two additional layers on basic device that is IBC solar cell: a silicon quantum dots (SiQD) layer and a plasmonic layer (PPL). We plan to utilize silicon nanocrystals as optical downshifter or down converters [1]. 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 colour will enhance the overall performance of the solar cell. A model of solar cell efficiency including this downshifting has been developed. Subsequent simulations on the basis of experimentally observed downshifting have lead to a projected efficiency enhancement of 10% relative.

A new approach is investigated in this project for SiQD layer: the silicon nanocrystals will be grown embedded in a passivated dielectric layer. This has two main advantages: unlike amorphous silicon, the SiQD layer does not suffer from long term stability issues [2], and there is evidence of multiple exciton generation for high energy incident photons [3].

The second novel light-matter interaction exploited is in the field of plasmonics. This is a novel method for increasing light absorption [4], [5] 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 [6]. This can be used to enhance the performance of the SiQD 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 explored in LIMA project [7]. 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. 1. Schematic cross section of integrated LIMA device

3. Cost analysis and industrial feasibility

The industrial feasibility of the photovoltaic device developed in this project has been analyzed in three steps: the technical evaluation of processes and equipments required to manufacture this device at mass production level, the operational cost analysis of the technology and the economic assessment of the industrial exploitation. The technical evaluation of the process flow and manufacturing equipments is the backbone of the cost analysis. When the manufacturing processes and equipments are defined, the cost model is built adding the consumables, materials, power energy, and labour needed in each process step. Once the cost model has been developed the economic assessment can be obtained in terms of model assumptions. During the first year of the project 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 [8]. During 2011 the cost model has been readjusted because of the manufacturing cost of base technology has dropped dramatically: the key driver has been the reduction of silicon wafer cost, however other factors have been considered. The thickness of metallization grid has been reduced, so it is used less quantity of silver paste for frontal metallization. Besides the cost of module encapsulation has been reduced because of process developments. The use of Printed Circuit Boards have been introduced, so the automatization and the production yield have been increased.

3.1. Technical evaluation

As reference we start describing the standard silicon solar cell technology base on type-p monocrystalline Cz-Si wafer, alkaline texturing, phosphorous diffusion in quartz tube, antireflection (ARC) coating of silicon nitride by PECVD (Plasma Enhanced Chemical Vapor Deposition) and three-step screen-printing metallization (Ag in front, Ag/Al rear buses, Al rear). This device, identified as aluminum back surface field (BSF-Al) technology, is the reference technology at mass production scale. The IBC solar technology used is based on n-type Cz-Si wafer, boron diffusion process by liquid source (BBr_3), phosphorous diffusion for FSF and BSF and screen-printing metallization in a co-firing process.

The LIMA device is manufactured by integration of two novel layers: a silicon-rich-oxide (SRO) layer that leads to a SiQD layer after a properly annealing and a plasmonic layer. The optimized process flow leads to integrate the SRO layer annealing and the boron diffusion step, and leads to use the SRO/SiO_2 stack as antireflection coating. The plasmonic is deposited after metallization: silver deposition on the front side by PVD and an annealing about 300 – 400 ºC.

3.2. Cost model

To build up the cost model have been considered a complete list of equipments and its features, power energy consumption, personnel to operate them, materials and other details. The cost of standard technology based on p-type monocrystalline silicon solar cells and BSF-Al device have been estimated as reference. The main assumptions have been the following:

- 50MW production line size that working with three shifts
- Ten years for depreciation time of equipments
- Electricity cost average is 0.110 €/kWh [9]
- 156 mm x 156 mm Cz-Si wafer price is assumed as 1.22 €/piece [10]. This means the wafer price has dropped 56% in less that 1.5 years, from August 2010 to January 2012.
- An average efficiency of 17.5% at mass production level is assumed for BSF-Al technology.

The first results calculated during 2010 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 was considered as reference for solar cell efficiency of 17.5%. After the model has been readjusted, the average cost per watt for standard photovoltaic module based on BSF-Al solar cell is 0.84 €/Wp. These results and cost breakdown for standard technology is shown in figure 2.

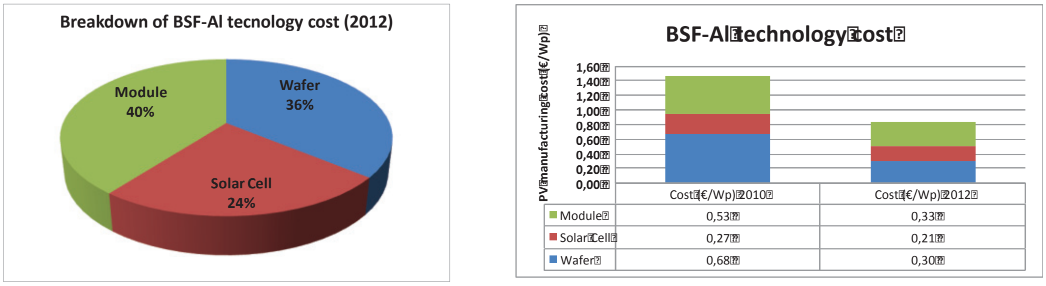

Fig. 2. (a) Cost breakdown for photovoltaic module based on BSF-Al solar cell technology; (b) cost reduction in standard technology in less than two years.

If we assume 19.0% as solar cell efficiency average for IBC technology at mass production level and 20.0% for LIMA technology and a scenario of 50 MW production line, the manufacturing cost is estimated as follow in table 1. Efficiency above 21.0% for IBC solar cell has been reported for large area solar cells. The cost reduction that comes from efficiency increase is shown in figure 3 (a), the manufacturing cost is dropped from 0.88 €/Wp to 0.80 €/Wp when efficiency increase from 19.0% to 21.0%.

Table 1. Breakdown of cost for photovoltaic module based on 19% efficiency IBC solar cell and 20% efficiency LIMA solar cells.

Breakdown of cost for photovoltaic module based on 19% IBC solar cells	€/Wp	%	Breakdown of cost for photovoltaic module based on 20% LIMA solar cells	€/Wp	%
Wafer (polysilicon + ingot growing + wafering)	0.28	32%	Wafer (polysilicon + ingot growing + wafering)	0.27	32%
Solar cell	0.26	30%	Solar cell	0.28	33%
Module encapsulation	0.34	38%	Module encapsulation	0.29	35%
Total	0.88		Total	0.84	

The comparison among technologies is shown in figure 3. The reduction of wafer cost has led to close the gap between IBC and LIMA technology. The efficiency threshold for LIMA solar cell technology is 20.0% to assure the industrial viability of the technology developed in this project. Moreover, it is needed to demonstrate during third year of the project (2012) that LIMA technology increase 5% the efficiency of the underlying IBC technology.

The manufacturing cost for 500 MW – 1 GW factory scale has been explored using several correction factors to estimate the cost saving coming from economy of scale available in the bibliography [11]. We have considered that the wafer manufacturing cost could be reduced in range from 25% to 35%, screen-printing pastes in range from 30% to 40%, rest of material for solar cells and modules in range from 10% to 20%, we have considered a cost saving from 30% to 40% in labour, from 20% to 30% in equipments and from 40% to 50% in fixed costs. This cost saving is based on that 1 GWp factory has higher volume of row material purchases, higher level of automatization, some materials may be produced on site, using a large number of similar manufacturing systems make easier the process engineering so an increase of production yield is expected and a reduction of engineering cost, the rest of indirect cost may be reduced, for example the department of purchase, administration, sales, R&D, etc. because of their weight in the global cost is reduced.

The impact of economy of scale related to photovoltaic module manufacturing cost from the 50 MWp scenario to the 1 GWp scenario has been explored. The manufacturing cost for photovoltaic module drops to 0.58 €/Wp when we assumed 17.5% as average efficiency at industrial level for BSF-Al solar cell and 20.0% as average efficiency at industrial level for LIMA technology. These results are shown in figure 3 (b).

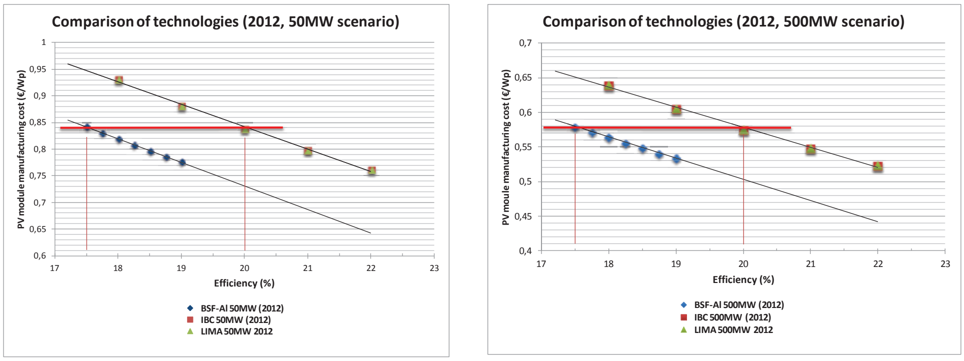

Fig. 3. (a) Comparison of technologies for 50 MW production scale scenario; (b) comparison of technologies for 500 MWp – 1 GWp production scale scenario

3.3. Economic assessment

Once the cost model is built, we can compare the three technologies from the point of view of the economic assessment. Both scenarios 50 MWp and 1 GWp factory have been considered. Data output of economic assessment are based on two parameters:

- The Return of Investment (ROI) is defined as the time (in years) is needed to balance the investment cost and the profits.
- The differential profit is referred to the profits of BSF-Al technology

The result of economic evaluation for 50 MWp scenario is shown in table 2. We have considered an average sale price of 1.0 €/Wp for 50 MWp scenario. The IBC technology obtains profits 19% lower than standard technology. The ROI for IBC and LIMA technology are significantly higher than BSF-Al technology. However, profits for LIMA technology are an 18% higher. If we consider an average efficiency at industrial level for LIMA solar cell technology two point more, that is 22.0%, the impact on economic results are evident: the ROI is lower than standard technology and the annual profits are nearly the double.

Table 2. Economical assessment for 50 MWp and 500 MW- 1 GW scenario. APD: annual profit differential

50MW scenario	Manufacturing cost (€/Wp)	ROI (years)	APD	500 MW- 1 GW scenario	Manufacturing cost (€/Wp)	ROI (years)	APD
BSF-Al (17.5%)	0.84	2.6	-	BSF-Al (17.5%)	0.58	1.3	-
IBC (19.0%)	0.88	4.8	-19.0%	IBC (19.0%)	0.61	2.0	-4.0%
LIMA (20.0%)	0.84	4.0	18.0%	LIMA (20.0%)	0.58	2.0	16.0%
LIMA (22.0%)	0.76	2.5	90.0%	LIMA (22.0%)	0.52	1.5	58.0%

The result of economic evaluation for 1GWp scenario is shown in table 2. We have considered an average sale price of 0.8 €/Wp for this scenario. The IBC technology obtains profits 4% lower than standard technology while LIMA technology gets 16% more profits than BSF-Al technology. In 1 GWp scenario, two points higher in average efficiency at mass production level implies a relevant reduction of the ROI from 2.0 to 1.5 years while annual profits increased by 58%.

4. Conclusions

A novel third generation device based on IBC solar cells and two additional layers on top have been presented. The novel layers are a SiQD 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 BSF-Al technology, IBC technology and advanced device based on IBC with SiQD layer and plasmonic layer. And finally, an economical assessment of these technologies at industrial scale has been carried out.

In this paper two scenarios of production size have been analyzed: 50 MWp and 500 MWp – 1 GWp.

The cost model shows the technology developed in LIMA project is industrially feasible when 20% solar cell efficiency is demonstrated at mass production level and when 5% of relative increase of efficiency is demonstrated above the level of the underlying IBC technology.

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References

[1] F. Sgrignuoli, G. Paternoster, A. Marconi, P. Ingenhoven, A. Anopchenko, G. Pucker, L. Pavesi. Modeling of Silicon Nanocrystals Based Down-Shifter for Enhanced Silicon Solar Cell Performance. Journal of Applied Physics 111, 034303 (2011).

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

[3] 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).

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

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

[6] 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.

[7] J. P. Connolly, et. al. Analysis of plasmonic nanoparticle fabrication techniques for efficient integration in photovoltaic devices. Proc. 25th European Photovoltaic Specialists Conference, Valencia September 2010.

[8] M. A. Vazquez, et al. Cost Model for LIMA device. Energy Procedia, Volume 8, 2011, Pages 443-448. Proceedings of the Silicon PV 2011 Conference (1st International Conference on Crystalline Silicon Photovoltaics) doi:10.1016/j.egypro.2011.06.163

[9] Source Eurostat. UE-15 industrial electricity price for 2011.

[10] http://pvinsights.com, 20th January 2012.

[11] C. del Cañizo, G. del Coso and W. C. Sinke. Crystalline silicon solar module technology: towards the 1€ per watt-peak goal. Prog. Photovolt: Res. Appl. (2008). DOI: 10.1002/pip.878.