View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Elsevier - Publisher Connector

ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Physics Procedia 2 (2009) 751–757

Physics Procedia

www.elsevier.com/locate/procedia

Proceedings of the JMSM 2008 Conference

Cost-effective photovoltaics with silicon material

M. Fathi*, A. Mefoued, A. Messaoud, Y. Boukennous

Silicon Technology Unit (UDTS), 2 Bd Frantz Fanon, BP.140 Alger-7 Merveilles, Algiers 16200, ALGERIA

Received 1 January 2009; received in revised form 31 July 2009; accepted 31 August 2009

Abstract

In this study, we have analysed the new emerging technologies in the field of photovoltaic (PV) and their impact on the finale cost of the solar cells. We have compared the 2 main groups of PV solar cells which are bulk silicon (Si) and thin-film. The aim of this project is the establishment of the technology roadmap for achieving Si solar cells at a competitive manufacturing cost. This goal can be achieved by using cheaper multicrystalline Si (mc-Si) wafers, thinner Si substrates (below 200µm), better front and back surface passivation, improved screen printing, and surface texturing.
© 2009 Elsevier B.V. Open access under CC BY-NC-ND license.

PACS: Type pacs here, separated by semicolons ;

Keywords: silicon, solar cells, photovoltaics, passivation, screen printed contacts.

1. Introduction

For this century, the challenge number one for the world is the energy. Also, there are other problems to solve such as: climatic change, environment degradation, CO2 emission and strategic control of the energy sources. All of these cited problems are linked to the choice of the energy source and its availability. As the fossil energy continues to dominate the world, new sources of energy have emerged and there is a growing interest around “clean and renewable energy” such as solar energy wind or biomass. These renewable energies are the solution to the world challenge for energy.

The solar energy can be a main part of the solution to this world challenge. The solar energy can be used either by thermal or photovoltaic transformation. In this study we will focus on photovoltaic (PV) solar energy area. More precisely, we will study the place of silicon material and its competitiveness with other PV materials. Thus, our interest is around the raw material and associated processes for the PV devices.

These last years (1996–2007), the PV market exploded and grew at an average rate of 30–35% per year, thus conducting to the problem of availability of silicon feedstock for solar cells. The long-term success of silicon PV application will require a drop below $1/W of silicon solar cells in order to compete with conventional sources of

* Corresponding author. Tel.: +0-213-21-43-35-11 ; fax: +0-213-21-43-24-88.
E-mail address: dr_fathimohamed@yahoo.fr .

doi:10.1016/j.phpro.2009.11.021

energy. For reaching this goal, we have performed a detailed cost analysis of several technological scenarios for processing of Si PV solar cells.

2. Photovoltaic market and technology trends

This year (2008), PV market reaches 6 billion euros and it should reach 31 billion in 2011 and 60 billion in 2020 [1]. The production of photovoltaic cells passed to 3.8 GW in 2007, an increase of 50 percent approximately compared to 2006. It is the source of energy which presents the fastest growth at the world! The figure 1 represents this fast progress.

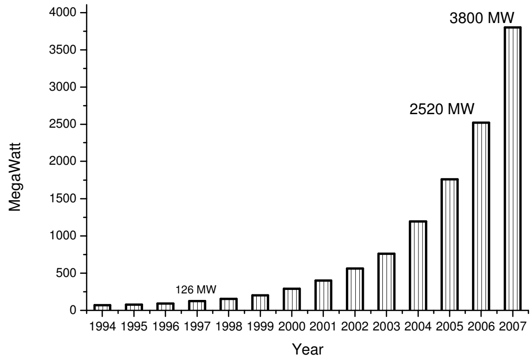

Fig. 1. Photovoltaic market trends

The figure 2 describes the average cost of PV module from 1975 to 2007. The average cost of PV module was 99.61$ in 1975 (for a total world production of 2 megawatts) and it decreased to 3.84$ in 2006 (for a total world production of 2521 megawatts).

For the terrestrial applications of PV, there are mainly two classes of cells: ‘bulk Si’ solar cells and ‘thin film’ solar cells. ‘Bulk Si’ solar cell or commonly called ‘Si’ solar cells are based on the use of a Si substrate (wafer) which can be of monocrystalline or multicrystalline type [1]. It represents 89% of the cells marketed in the world in 2007. The wafer of multicrystalline silicon type is cheaper than monocrystalline but it has a high density of grains boundaries and crystalline defects which necessitate specific electrical passivation. Thin film solar cells are obtained from deposition of thin film semiconductors on cheaper substrate (i.e. glass, polymers, etc...).

For the bulk Si group, the strong growth rate of PV market has conducted to a deep crisis on the provisioning of the raw material (polysilicon of solar grade: SoG). The price of this material passed in a few years from 20 $/Kg to 65 $/Kg. It should be noted that SoG is elaborated from the metallurgical silicon (2 $/Kg) which itself is obtained from the silica of high purity. This crisis pushed important firms to invest in the production of SoG. These high levels of investment will attenuate the situation of silicon shortage. But, it strongly stimulated the interest to the PV cells of thin film family.

In the case of thin film PV cells, there are mainly two types of cells which are CIS (Copper-Indium-Selenium) and those with amorphous or microcrystalline silicon [2]. These cells use a negligible quantity of semiconductor material deposited on a cheaper substrate which reduces their cost. The efficiency of CIS cells is rather high; to date one will note efficiency of 19% in laboratory and 11% in production. As for the cells with amorphous silicon, their efficiency is 13% in laboratory and 9% in production. The cells in thin layers have the characteristic to be able to be integrated on a flexible support and can be used for the mobile applications (computers, watches, battery chargers, etc...).

The solar cells of thin film technology settles more and more in the landscape of photovoltaic and this even if their efficiency remains lower than Si PV cells. In 2000 the share of market of the thin film was only 4.8% of the total production of the solar cells (in MW). Under the effect of the shortage of SoG, the production of the thin cells layers continued to progress and arrived at 400 MW in 2007 (more than 10% of PV world market). At the end of the year 2008, 1GW of solar cells in thin film will have been produced and according to the Prometheus institute a projection of 10 GW for 2012 is possible [1].

World leaders of solar thin films have reached costs around 1.25$/W and projects to reduce them to less than 1$/W into 2009 thus approaching the parity with fossil energy [3]. Now, the question is how Si solar cells can continue to dominate the market and be cost efficient to this new thin film PV cells?

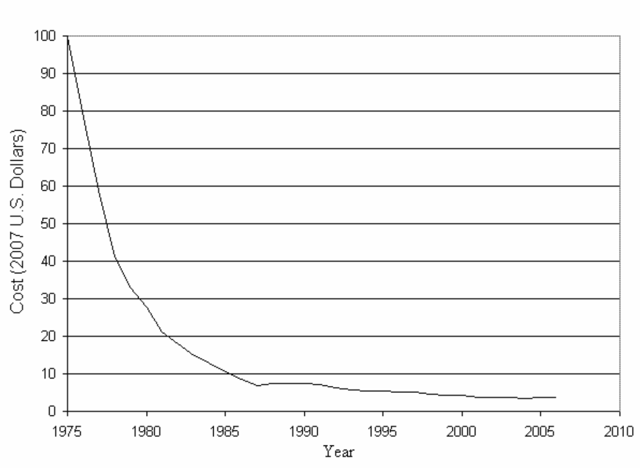

Fig. 2. World average PV module cost per Watt, 1975-2007

3. Cost Analysis of photovoltaic cells with bulk silicon technology

The sequence for manufacturing crystalline silicon modules is broken into major process groups, as shown in figure 3. The processing of silicon solar cells begins with the growth of the silicon ingot, slicing the ingot into wafers, processing wafers into solar cells, and interconnecting the cells into circuits and completing the assembly of a framed and packaged module ready for shipment. The cost breakdown of the major groups is essentially equivalent, as shown in figure 4, with each major processing area contributing between 20 and 30%. A comprehensive cost study conducted under the European Photovoltaic Programs [4] showed that for 500 MW production of screen-printed of monocrystalline CZ and multicrystalline Si cells with efficiencies of 16% and 15% can reduce the manufacturing cost to 1.25€/W and 0.91€/W, respectively. More recently [5], this study was reviewed to validate these results and it was concluded, based on the progress in the past five years, that 150µm thick, 17% efficient screen printed multicrystalline Si (mc-Si) are achievable in the future at a manufacturing cost of 0.77€/W for 500MW production. The US Department of Energy (DOE) with PVMaT project also estimates a current direct manufacturing cost of $2/W for crystalline Si modules and projects that it will drop to $1/W by 2009-2010. Thus several cost studies have indicated that the direct manufacturing cost for crystalline Si PV modules has reached ~$2/W, with strong potential for reduction below $1/W.

The current purified polysilicon feedstock shortage has recently driven up prices of the silicon substrate, which was already a major portion of the cell cost. But substrate prices are likely to recover in 2009-2010 as additional polysilicon feedstock manufacturing capacity comes on line. The increased cost of silicon has driven innovation in cell processing. Lower wafer thickness, higher efficiency and yield will accelerate the move to a new lower cost baseline Si solar cell when the polysilicon feedstock price comes back down. On the other side, Research and Development groups in the world are currently focused on cost decrease of Si PV cells through the following action:

- Reduction of materials cost and particularly for the silicon substrate,
- enhancing energetic conversion efficiency,
- Improving manufacturing processes throughput,
- Improving processes yields (tighter performance distributions, recycling of defective cells, and reducing wafer breakage).

The table 1 gives the impact of the processing steps parameters of Si solar cells and polysilicon price on the PV module manufacturing cost ($/W).

Table. 1: Modules manufacturing cost versus main processing parameters and polysilicon price

Processing parameters	polysilicon price = $45–60/kg	polysilicon price = $20/kg
Wire sawing	$0.25/W	$0.15/W
Wafer size	~250 cm^2	~400 cm^2
Wafer thickness	200–250µm	120 µm
Volume manufacturing	100–200 MW/year	500 MW/year
Automation	Partial	Complete
Efficiency, commercial modules	12%–18%	15%–21%
Module manufacturing cost	**$2/W** (Polysilicon at **$30/kg)**	**$1/W**

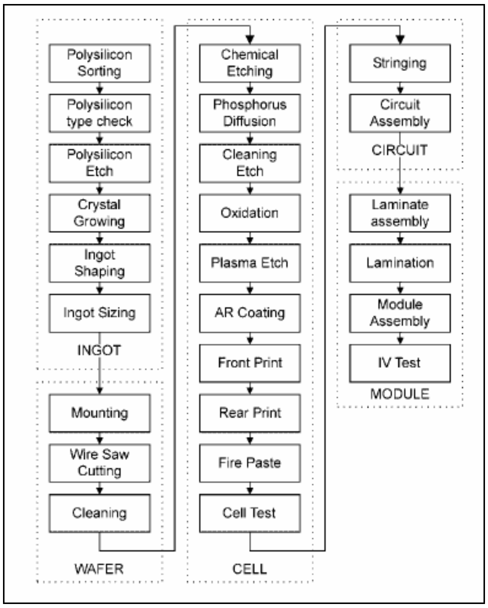

Fig.3. Manufacturing steps of crystalline silicon PV modules.

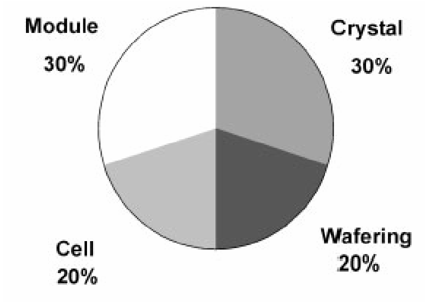

Fig. 4. Manufacturing cost by process area

4. Discussion of the technology roadmap for achieving a cost effective Silicon solar cells

In order to lead some of the identified technological actions (see section 3) and related to the cost decrease of Si PV module manufacturing. We are going to describe the possible technological processing scenarios for a cost effective Si solar cell. In order to have more visibility in Si PV technology road map, we have applied PC1D simulation program [6]. This permitted us to calculate the efficiency and fill factor of a typical industrial Si solar cell realized with screen-printed contacts on p type Si. In order to take in consideration optical phenomena of surface reflection, we have also simulated effect of both planar and textured cells. On table 2, we have reported technological parameters and resultant characteristics of the studied Si solar cell by PC1D software.

Table. 2. PC1D calculation of electrical performance (Fill factor and efficiency) for Si solar cell

Si Solar cell technological parameters	Parameters values
Bulk resistivity	1.3 Ω.cm
Bulk lifetime	20 µs
Thickness	300 µm
Sheet resistivity	40 Ω/□
Front surface recombination velocity	$2.5\ 10^5$ cm/s
Back surface recombination velocity	10^6 cm/s
Antireflection coating	SiN_x
Metallization coverage	8%
Result of PC1D Simulation: Characteristics of Si solar cell	Fill factor = 0.74, Efficiency = 13.5%

For the simulated standard Si solar cell with a 20µs bulk lifetime and 300 µm wafer thickness we obtained 13.5% efficiency. By varying PC1D inputs and in order to achieve Si solar cell of 17–18% efficiency, we established that there are needs in improvement of five technological parameters. These are:

1) Wafer thickness: to reduce from 300 to 200µm
2) Back surface field (BSF): to reduce the front surface recombination
3) Selective emitter and 80Ω/□ sheet resistance of diffused n+ emitter: to reduce the front surface recombination
4) Fine-line screen-printed contacts: to reduced shading losses from 8% to 5%
5) Surface texturing: to increase light absorption

The figure 5 represents the structures of high efficiency Si solar cells [7]. Here after, we will explain the function of each part of this type of Si solar cell, as described before for performance improvement in 5 technological parameters. The reduction in the Si solar cell thickness contributes at the same time to reduce the cost of a solar cell and increase the conversion efficiency. The most obvious approach to do this is to slice thinner wafers so that more wafers can be obtained from an ingot, therefore reducing the price per wafer. In the last years, the thickness of wafers used in the industry has reached a standard thickness around 200 micrometers. It is anticipated to affirm that this trend will continue. But, it is possible that the next generation of PV module will be based on two-sided cells made with very thin wafers (~100-150µm thick).

Aluminum-Back Surface Field (Al-BSF) is realized on the rear side of the Si cell and where Si is highly doped with Aluminum in order to form p^+ region as a result of an alloying and re-growth process during a thermal anneal. This p^+ area create an electrical field to accelerate the collection of charge carriers. The screen-printed Al-BSF has been shown to improve appreciably its effect when a fast ramp-up rate is implemented during Al-Si alloying [8, 9]. Effective back surface recombination velocity values of 200 cm/s have already been reported for screen-printed Al-BSF formed on 2 Ω.cm float zone Si [9]. However, as we move toward thinner wafers, the conventional Al-BSF formation may not be suitable as it warps thin wafers. Then, we have to develop a good dielectric back surface passivation scheme, or cost effective boron BSF. Back Surface Recombination Velocity (BSRV) values in the range of 1–100 cm/s have been reported [10] for dielectric passivation of 1.3 Ω.cm single crystal Si, but a considerable challenge remains in achieving such low BSRV values for multicrystalline Si (mc-Si) due to defects at the silicon/dielectric and p/p+ interface. To achieve this, the rear structure of the mc-Si solar cell has to be modified. Instead of the conventional Al-BSF, the rear surface has to be passivated with a dielectric layer, and the cell has to be locally contacted. The rear side passivation should also provide the right properties in terms of thermal stability and internal reflection. The passivation of the rear surface is obtained with a stack of silicon oxide and PECVD nitride. For the local contacts, openings can be made in the rear passivating layer by laser ablation and a local alloying process with Al in the openings creates the local contact with a small back-surface field region underneath, limiting recombination at the rear contacts.

The surface passivation by oxide/Si nitride stack has been investigated in detail [11]. It was shown that hydrogen (H) plays a crucial role in the surface passivation process. During the rapid thermal process (RTP) of screen-printed contacts, hydrogen diffuses from the SiNx:H surface passivation layer towards the $Si\text{-}SiO_x$ interface and passivates defects such as Si dangling bonds [11]. For economic considerations, 80% of Si PV solar cells are using cheaper mc-Si wafers. This conducts to the need of surface passivation step in order to reduce surface recombination phenomena. The surface recombination effect is mainly du to crystalline defects. N^+ emitter region is formed by the diffusion of Phosphorus impurities (P); these P impurities will induce distortions of Si crystalline order. By decreasing N^+ diffusion concentration, we contribute to have a lower crystalline defects density. Then, it was established [12] that for economical mc-Si we have to use a 80Ω/□ sheet resistance of diffused n^+ emitter, much higher than in case of conventional monocrystalline silicon (40Ω/□). On the other hand, these higher values of sheet resistance (80Ω/□) imply a higher resistance contact at the interface metal/semiconductor. Thus, we need to have locally under front contact metal a higher diffusion (n^{++}), this is known as a selective emitter [12].

By producing fine-line screen-printed contacts, the shading loss is reduced. Actually, the screen printing equipment permits to have higher definition of front contact gird lines. This contributes to a lower shading loss and a higher efficiency. Now, screen printing masks can be grooved by laser technique which contributes to have fine pitch lines of 50 µm in the stat of the art [12]. In order to maximize solar cells efficiency, the front surface has to be textured [13]. Chemical and plasma texturing process have been developed. By combining several of these processes, mono-Si solar cells have reached 18% in production line. The mc-Si cells are around 16% in industry, and will continue to progress by innovative solutions. Actually, the R&D groups around the world are much working for developing Si solar cells with mc-Si wafers than mono-Si because of their lower cost.

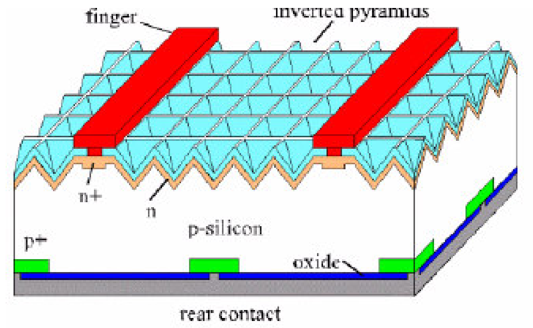

Fig. 5. Structure of a High efficiency Si solar cell.

5. Conclusion

Solar cells of bulk Si technologies will continue to offer a good balance between cost and performance. Meanwhile, thin-film technologies are growing very fast, but these suffer from lower efficiencies and low stability. Our cost analysis shows that the current manufacturing cost of bulk Si modules has reached \$2/W and can go below \$1/W to compete with traditional energy sources. This will require usage of multicrystalline Si wafer type with 150–200μm thickness, 17–18% cells efficiency and production lines scalable in 100–500 MW/year. These goals can be achieved with thinner Si substrates, modest bulk lifetime, better back surface passivation, improved screen printing, and surface texturing. Considerable progress has been made in each of these areas and efficiencies approaching 17–18% have been achieved in the production line of Si based screen-printed cells. The increased cost of the silicon feedstock: SOG has stimulated innovation in solar cell design and industrial investments in SOG production that will accelerate the move to a lower cost baseline.

6. References

[1] Prometheus Institute, PV News 26 (2007) 6-8
[2] J. Càrabe, J.J. Gandia, Optoelectronic review12(1) (2004) 1-6
[3] A. Rohatgi,J.-W. Jeong, Appl. Phys. Lett. 82 (2004) 224
[4] T.M. Bruton, G. Luthardt, K.-D. Rasch, K. Roy, I.A. Dorrity, B. Garrard, L. Teale, J. Alonso, U. Ugalde, K. Declerk, J. Nijs, J. Szlufcik, A. Räuber, W. Wettling, A. Vallêra, Proc.14th EC PVSEC (1997) 11-16
[5] N.B. Mason, T.M. Bruton, M.A. Balbuena, Conference Record of PV in Europe (2002)
[6] A. Kranzl, R. Kopecek, K. Peter, P. Fath, 4th World Conference on Photovoltaic Energy Conversion 1 (2006) 968-971
[7] S. H. Lee, Journal of the Korean Physical Society 39 (2001) 369-373
[8] W. Jooss, B. Fischer, P. Fath, S. Roberts and T.M. Burton, Proc. 3rd World Conf on Photovoltaic Energy Conversion, Vol. 1 (2003) 959-962
[9] A. Rohatgi, V. Yelundur, J. Joeng, A. Ristow, A. Ebong, Proc. 10th Work shop on Crystalline Silicon Solar Cell Materials and Processes 12 (2000)
[10] A. Rohatgi, P. Doshi, J. Moschner, T. Lauinger, A.G. Aberle, D.S. Ruby, IEEE Transactions on Electron Devices 47 (2000) 987-993
[11] W.H. Lin, K.L. Pey, Z. Dong, S.Y.-M. Choi, M.S. Zhou, T.C. Ang, C.H. Ang, W.S.Lau, J.H.Ye, Electron Device Letters, IEEE 23 (2002) 124–126
[12] D. S. Kim, E.J. Lee, J. Kim and S.H. Lee, Journal of the Korean Physical Society 46 (2005) 1208-1212
[13] M. Schnell, R. Ludemann, S. Schaefer, Photovoltaic Specialists Conference, Conference Record of the 21th IEEE (2000) 367-370