Plasma Processing Solutions to Challenges in High-Efficiency Silicon Solar Cell Fabrication

G. Fischer[1,2], **R. Léal**[3,2], R. Peyronnet[1,4], E. Drahi[3,1], G. Poulain[3], M. Lemiti[4], E. V. Johnson[2,1], P. Roca i Cabarrocas[2,1]

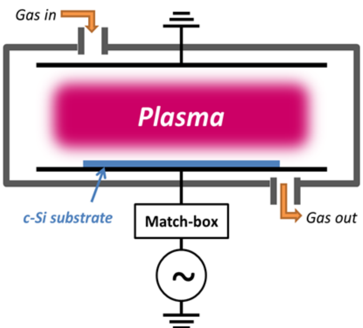
[1]Institut Photovoltaïque d'Ile-de-France (IPVF), 8 rue de la Renaissance, 92160 Antony, France
[2]LPICM, CNRS, Ecole Polytechnique, Université Paris-Saclay, 91128 Palaiseau, France
[3]Total MS-Energie Nouvelles-24 cours Michelet, La Défense 10, 92069 Paris la Défense Cedex, France
[4]Institut des Nanotechnologies de Lyon (INL), 20 Avenue Albert Einstein 69621 Villeurbanne, France

Introduction

Photovoltaic (PV) energy is a key component of any new energy mix targeting sustainable development[1]. Considerable efforts are currently made in the field of silicon (c-Si) solar cells to increase efficiencies at ever lower manufacturing costs.

Progresses arising from two innovative plasma techniques, namely **plasma texturing** and **low-temperature plasma assisted epitaxy**, are particularly under investigation at the Institut Photovoltaïque d'Ile-de-France (IPVF). Considerable scientific challenges and economic opportunities are anticipated when combining these key technological blocks with the aim of manufacturing thin (~100µm) high efficiency c-Si solar cells.

Plasma processes use ionized gases to either etch, deposit or convert a layer of material. They are usually referred to as "dry techniques" in opposition to "wet techniques" (the latter involving treatments in liquid solutions).



Crucial advantages of dry techniques for future developments in PV industry:

- Process thin (~100µm) substrates
- Decrease use/loss of raw c-Si material
- Reduce number of processing steps
- Avoid bulk degradation (thanks to low-temperature)

Dry techniques have major drawbacks though, among them:

- Costs of vacuum systems
- Treatment of gaseous by-products (including greenhouse gases)

Fig. 1: Simplified schematic of a standard plasma etching system. The substrate electrode is powered to increase the ion bombardment energy (IBE) for etching. For deposition, the counter-electrode is usually powered to keep IBE on substrate low.

Surface nanotexturing

- *Description of the technique:*

  SF_6/O_2 **plasma etching** of c-Si with proper parameters → Nanotexturing
- *Objectives:*
  - Drastically decrease reflectance of front surface (below 1%) → increase of photogenerated current density (J_{phgen})
  - Avoid the use of chemical steps and the addition of an anti-reflective coating
  - Reduce material losses (manufacturing thin c-Si solar cells)

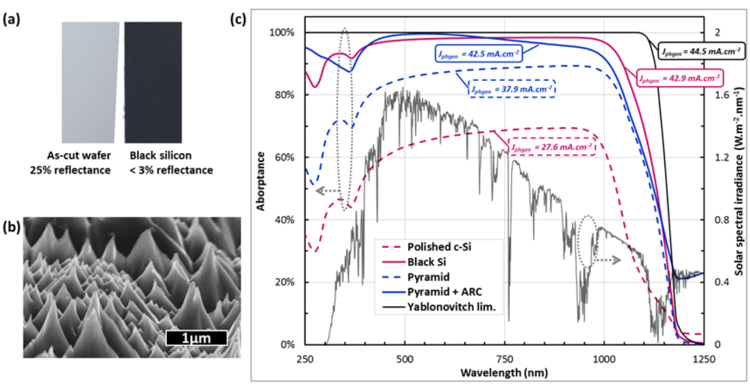


Fig. 2: (a) Picture of a bare silicon samples (left) and a black silicon sample (right). (b) Scanning electron microscopy of black silicon nanotextures. (c) Comparison of the absorptance of polished Si, black Si, pyramid textured Si, pyramid textured Si with ARC, and theoretical Yablonovitch limit, along with the solar spectral irradiance. Photo-generated current densities (J_{phgen}) are given for comparison.

- *Remaining challenges:*
  - Mechanisms of nanotexturing = still unclear[3]
  - Record efficiency for a solar cells with nanotextured surface = 22.1%[2], (only 0.1% above reference without nanotexturing)
  - Poor surface passivation possibilities[3], i.e. high electron-hole recombination losses near the surface!

Low-temperature plasma assisted epitaxy

- *Description of the technique:*

  Low temperature **plasma assisted crystalline growth**[4] for the formation of doped layers → Separation of charge carriers in the cell
- *Objectives:*
  - Simplifying the process flow by reducing the number of steps in solar cell manufacturing
  - Limiting high temperature process steps and optimizing doping profile in p-doped silicon

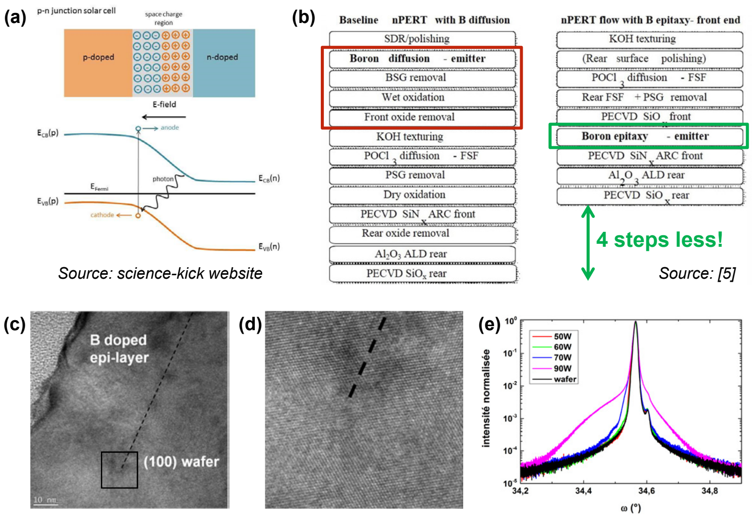


*Fig. 3: (a) Process flow of the n-PERT solar cell with **p-type** layer formation by standard boron diffusion and innovative boron-doped epitaxy. (b) Transmission electron microscopy image of **boron-doped epitaxial layer grown at 200°C by PECVD.** (d) Zoom on the interface highlighting the excellent quality of the epi-layer. (e) X-ray diffraction scans for different plasma power. The increase of power enhances the deposition rate but decreases the crystalline quality.*

- *Remaining challenges:*
  - Improving electrical properties in spite of excellent structural properties
  - Increasing deposition rate to provide an industrially viable technical solution

Perspectives & Challenges

Presented below is the architecture that would allow the combination of the techniques: n-PERT with front surface nanotexturing and rear surface epitaxial emitter.

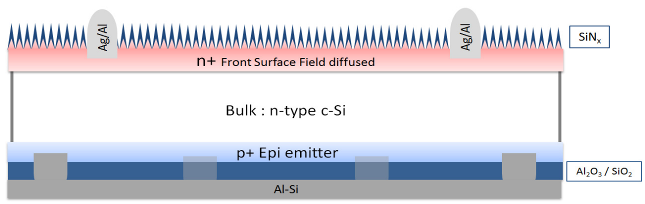


Fig. 4: Cross section of n-PERT Solar cell including both process steps (not to scale).

Combination of the 2 techniques on the same side of the cell is still challenging:

- Bifacial cell not possible.
- No epitaxy of front surface field layer.

References

[1] ADEME, Vers un mix électrique 100% renouvelable en 2050, April 2015.
[2] Savin *et al.*, "Black silicon solar cells with interdigitated back-contacts achieve 22.1% efficiency," *Nat. Nanotechnol.*, May 2015.
[3] Gaudig *et al.* "Properties of black silicon obtained at room-temperature by different plasma modes," *JVSTA*, 33, 5, Sep. 2015.
[4] Cariou *et al.*, "Low temperature PECVD epitaxial growth of silicon on GaAs : A new paradigm for III-V/Si integration". *Sci. Rep.*, May 2016
[5] Kuzma-Filipek *et al.*, "Integration processes for nPERT Si solar cells using single side emitter epitaxy and front side laser doping", *Energy Procedia*, Aug. 2015.