“Cost-effective technologies for crystalline silicon (c-Si) solar cells”

Dr. Isidro Martín
(isidro.martin@upc.edu)

11th February 2014
Outline

1. Introduction, description of the problem and objectives

2. Laser processing applied to rear contact schemes
   - Laser fired contacts with Al films
   - Laser doped regions from dielectric films: $\text{Al}_2\text{O}_3$ and $\text{SiC}_x(n)$ films.

3. Fully low temperature structures
   - DopLa (Doped by Laser) cell.
   - IBC (Interdigitated Back Contacted) cell.
   - Silicon Heterojunction solar cells.

4. Very thin c-Si wafers: mille-feuille concept

5. Resources

PROGRAMA DE DOCTORAT EN ENGINYERIA ELECTRÒNICA

Jornades formatives 2014: Projectes de recerca al Departament d’Enginyeria Electrònica
Photovoltaic effect

Electron contact (n+ semicond.)
Hole contact (p+ semicond.)
Many technologies involved
Terrestrial applications market

- **Costs** is a driving force (€/Wp)
- Crystalline silicon shares more than 80% of the market

Crystalline silicon shares more than 80% of the market, with High quality c-Si being the dominant type. Low quality c-Si is also present but with a smaller share. The graph illustrates the market share of different types of solar cells from 1999 to 2009, with a focus on the high-quality c-Si cells.
Very simple fabrication process

Main costs:
- c-Si wafer.
- High temperature steps for the creation of the highly-doped regions.
Thinner wafers

Silicon is about the 40% of the cost

Reduction of the wafer thickness

Source: SiGen
Problems with full Al p+ contact

Scenery of the commercial c-Si solar cells:

- Limited by the surface recombination at the back contact

- Thinner substrates

- Lower costs (more wafers per ingot)

- $L_D > W$

$S_{eff} \sim 10^4 \text{ cm/s}$
Adaptation of PERL concept to thin industrial substrates

- Applied to the world record c-Si solar cell (24.7%, UNSW).
- Rear side passivation based on dielectric layer and point contact.
- Dielectric film ($\text{SiO}_2$) thermally grown at $\sim 1100^\circ\text{C}$ 😄
- $p^+$ regions created by high temperature step 😍
- Definition of the contacts by lithography 😍

MNT activities in c-Si solar cells

**Main objective:** development of cost-effective technologies to create p+ and n+ regions and compatibles with thin substrates.

Laser processing applied to rear contact schemes:
- p+ regions: laser fired contacts with Al and Al$_2$O$_3$ films.
- n+ regions: laser doping from SiC$_x$(n) films.

Fully low temperature structures:
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Fabrication of very thin c-Si wafers, the “Mille-Feuille” concept.
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Base line process

We use it as a reference technology, based on PERC structure (Passivated emitter and rear contact).

- Texturization by inverted pyramids.
- POCl\textsubscript{3} diffusion (850 °C).
- SiO\textsubscript{2} passivation (1070 °C).
- Front and back contact defined by lithography

<table>
<thead>
<tr>
<th>(V_{oc}) (mV)</th>
<th>(J_{sc}) (mA/cm\textsuperscript{2})</th>
<th>FF (%)</th>
<th>(\eta) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>628</td>
<td>39.0</td>
<td>75.9</td>
<td>18.6</td>
</tr>
</tbody>
</table>
**Laser Fired Contacts**

Replacement of lithography for the rear contact definition by Laser Fired Contacts (LFC).

Best result (1 mm pitch on p-type 0.45 Ω cm c-Si):

<table>
<thead>
<tr>
<th>$V_{oc}$ (mV)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>670</td>
<td>38.4</td>
<td>80.5</td>
<td>20.7</td>
</tr>
</tbody>
</table>

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c-Si surface passivation

We want to replace thermal SiO$_2$ by low temperature deposited films

- **PECVD:** a-SiC$_x$, a-SiC$_x$N$_y$ and a-SiC$_x$(n)

  $S_{\text{eff}} < 12 / 7 \text{ cm} \cdot \text{s}^{-1}$, for 1 $\Omega \cdot \text{cm}$ p/n type planar FZ c-Si substrates.

  On industrial 1 $\Omega \cdot \text{cm}$ p-type CZ silicon, $S_{\text{eff}} = 220 \text{ cm} \cdot \text{s}^{-1}$ at 1 sun and passivation of 30$\Omega$/sq diffused emitters obtaining $J_{\text{oe}} = 250 \text{ fA} \cdot \text{cm}^{-2}$

- **ALD:** Al$_2$O$_3$

  $S_{\text{eff}} < 2 / 10 \text{ cm} \cdot \text{s}^{-1}$, for 2.2 $\Omega \cdot \text{cm}$ p type planar/texturized FZ c-Si.

  $S_{\text{eff}} < 1 \text{ cm} \cdot \text{s}^{-1}$, for 2.8 $\Omega \cdot \text{cm}$ n type planar FZ c-Si substrates.

Al$_2$O$_3$ and SiC$_x$(n) can simultaneously work as passivating films and dopant sources for laser processes.
Advanced concept: LFC

First approach:

- High power laser process to break through the dielectric film.
- Prone to create crystal damage.
- Laser processing screen-printed Al pastes is difficult to the dependence on the Al thickness.

Advanced concept:

- Low power laser process just to melt the c-Si surface and ablate the dielectric
- Less crystal damage
- Better back reflector properties
High quality p+ regions

Soft laser processes result in p+ regions with very low $S_{\text{rear}}$


PROGRAMA DE DOCTORAT EN ENGINYERIA ELECTRÒNICA

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Application to solar cells

<table>
<thead>
<tr>
<th>Cell</th>
<th>$\rho$ ($\Omega \text{cm}$)</th>
<th>pyramids</th>
<th>$p$ (µm)</th>
<th>$f_c$ (%)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>$V_{oc}$ (mV)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0.5</td>
<td>inverted</td>
<td>550</td>
<td>0.76</td>
<td>38.6</td>
<td>678</td>
<td>81.9</td>
<td>21.4</td>
</tr>
<tr>
<td>#2</td>
<td>2.3</td>
<td>inverted</td>
<td>450</td>
<td>1.13</td>
<td>38.6</td>
<td>640</td>
<td>82.1</td>
<td>20.3</td>
</tr>
<tr>
<td>#3</td>
<td>2.3</td>
<td>random</td>
<td>350</td>
<td>1.87</td>
<td>39.3</td>
<td>637</td>
<td>80.5</td>
<td>20.1</td>
</tr>
</tbody>
</table>

Better results than with conventional LFC process.

Good results also in 2.3 $\Omega \text{cm}$ substrates.

Main trend of the dependence of efficiency on pitch well modelled.

$\eta$ beyond 21%! (only about 10 labs in the world have reached this efficiency)

n\textsuperscript{+} regions by laser doping from SiC\textsubscript{x}(n)

Applied to the rear surface of n-type HIT solar cells (LPICM, INES)

The a-SiC\textsubscript{x}:H(n) is a stack of three layers:

- Rear surface passivation: a thin (2 nm) intrinsic Si-rich a-SiC\textsubscript{x}:H film is previously deposited onto c-Si surface.

- Doping source: next 15 nm of Si-rich film with a high phosphorus content (1.8% of PH\textsubscript{3} in gas phase).

- Back reflector and electric isolation: finally a dielectric a-SiC\textsubscript{x} film (n=2.0 and 80 nm) with phosphorus but in a much less percentage.
High quality n+ regions

<table>
<thead>
<tr>
<th>Rear configuration</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>$V_{oc}$ (mV)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
<th>$pFF$ (%)</th>
<th>$R_s$ (Ω cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amorphous BSF</td>
<td>30.25</td>
<td>696</td>
<td>74.8</td>
<td>15.7</td>
<td>82.9</td>
<td>2.24</td>
</tr>
<tr>
<td>SiCₓ + laser</td>
<td>30.05</td>
<td>672</td>
<td>72.5</td>
<td>14.6</td>
<td>80.5</td>
<td>2.22</td>
</tr>
</tbody>
</table>

I. Martín et al., presented at 27th EUPVSEC, Frankfurt (2012)
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n+/p and p+/n junctions

- n+ regions were formed from T=225 °C aSiC_x(n) stacks into p-type c-Si wafers.
- p+ regions are created from Al_2O_3/SiC_x stack into n-type c-Si wafers.

M. Colina et al., presented at 27th EUPVSEC, Frankfurt (2012)
DopLa cell concept

DopLa (Doped by Laser) cell: fully low temperature process without TCO

Al₂O₃+SiCx

1- Film deposition

p-type c-Si

d-Si(n)+SiCx

2- Laser processing

n-type c-Si

3- Metallization

n+ n+ n+ n+

p+ p+ p+ p+

p+ p+

n+ n+ n+ n+

n+ n+ n+ n+

p+ p+ p+ p+

p+ p+

n+ n+ n+ n+

n+ n+ n+ n+

p+ p+ p+ p+

p+ p+

n+ n+ n+ n+

n+ n+ n+ n+

p+ p+ p+ p+
DopLa cell geometrical characteristics

Main characteristics (1x1 cm² devices):
- Front surface: non-texturized surface, square matrixes with 1 mm pitch leading to 10 fingers.
- Rear surface: hexagonal matrixes with pitch ranging from 200 to 350 µm

Shadow factor:
- 10 fingers 120 µm wide (≈ 11.5 %)
- Triangular bus bar (≈ 1.3 %)

Shadow ≈ 12.8 %
DopLa cells on p-type substrates

I. Martin et al., presented at 28th EUPVSEC, Paris (2013)

<table>
<thead>
<tr>
<th>Pitch (µm)</th>
<th>J_{sc} (mA/cm²)</th>
<th>V_{oc} (mV)</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>26.5</td>
<td>634</td>
<td>75.4</td>
<td>12.64</td>
</tr>
<tr>
<td>250</td>
<td>25.5</td>
<td>634</td>
<td>72.4</td>
<td>11.62</td>
</tr>
<tr>
<td>300</td>
<td>24.8</td>
<td>635</td>
<td>66.5</td>
<td>10.47</td>
</tr>
<tr>
<td>350</td>
<td>25.2</td>
<td>636</td>
<td>59.4</td>
<td>9.52</td>
</tr>
</tbody>
</table>

same V_{oc}  
similar J_{sc}  
pitch
DopLa cells on n-type substrates

I. Martin et al., accepted in 4th SiliconPV, 's-Hertogenbosch (2014)
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IBC solar cell concept

Interdigitated Back-Contacted (IBC) solar cell: all contacts at the rear surface, so no front metallization shadowing. Commercially available by SunPower with high efficiencies (>23%).
IBC base line process

**Rear side (contacts side)**
Reference wafer

**Front side (illuminated side)**
Reference wafer

<table>
<thead>
<tr>
<th>Cell</th>
<th>Emitter coverage</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>$V_{oc}$ (mV)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td>86 %</td>
<td>41.0</td>
<td>652</td>
<td>75.0</td>
<td>20.0</td>
</tr>
<tr>
<td>#1</td>
<td>80 %</td>
<td>40.9</td>
<td>651</td>
<td>72.4</td>
<td>19.3</td>
</tr>
<tr>
<td>#4</td>
<td>75 %</td>
<td>40.6</td>
<td>648</td>
<td>77.2</td>
<td>20.3</td>
</tr>
<tr>
<td>#3</td>
<td>67 %</td>
<td>40.0</td>
<td>644</td>
<td>77.1</td>
<td>19.9</td>
</tr>
</tbody>
</table>

$\eta > 20\%$ in c-Si IBC cells! (only 5 labs in the world have reached this efficiency)
DopLa-IBC solar cell concept

Interdigitated Back Contact (IBC): definition of both p+ contacts and n+ emitters on the rear side of the cell. Patterning of the films by lithography and etching. No alignment of the laser needed. Fully low temperature.

1- Film deposition and patterning

2- Laser processing

3- Metallization
DopLa-IBC cell results

<table>
<thead>
<tr>
<th>$J_{ph}$ (mA/cm$^2$)</th>
<th>$V_{oc}$ (mV)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.4</td>
<td>564</td>
<td>60.3</td>
<td>7.3</td>
</tr>
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Oblea 0.45 $\Omega$cm
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HIT solar cell concept

Heterojunction with Intrinsic Thin film (HIT) solar cell: the n+ region is not created by high temperature diffusion but by deposition of phosphorus-doped amorphous silicon (a-Si) film. A thin intrinsic a-Si film is deposited in between to improve surface passivation.
HIT solar cell results

<table>
<thead>
<tr>
<th>Affiliation</th>
<th>η (%)</th>
<th>V_{oc} (mV)</th>
<th>J_{sc} (mA cm^{-2})</th>
<th>FF (%)</th>
<th>A (cm²)</th>
<th>Status</th>
<th>Year</th>
</tr>
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<tbody>
<tr>
<td>EPFL [123], Switzerland</td>
<td>19.7</td>
<td>717</td>
<td>37.9</td>
<td>72.7</td>
<td>4, FZ</td>
<td>–</td>
<td>2011</td>
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<tr>
<td>NREL [71], USA</td>
<td>19.3</td>
<td>678</td>
<td>36.2</td>
<td>78.6</td>
<td>0.9, FZ</td>
<td>IC</td>
<td>2010</td>
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<td>Titech [148]#, Japan</td>
<td>19.1</td>
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<td>0.8, FZ</td>
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<td>HZB [149], Germany</td>
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<td>36.8</td>
<td>79.1</td>
<td>1</td>
<td>PR</td>
<td>2009</td>
</tr>
<tr>
<td>Univ. Stuttgart [150], Germany</td>
<td>18.1</td>
<td>670</td>
<td>35.7</td>
<td>75.6</td>
<td>2</td>
<td>–</td>
<td>2010</td>
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<tr>
<td>LPICM [151], France</td>
<td>17</td>
<td>662</td>
<td>33.0</td>
<td>77.6</td>
<td>25, Cz</td>
<td>PR</td>
<td>2009</td>
</tr>
<tr>
<td>ENEA [152], Italy</td>
<td>17</td>
<td>601</td>
<td>37.1</td>
<td>76.3</td>
<td>2.25</td>
<td>PR</td>
<td>2004</td>
</tr>
</tbody>
</table>

$J_{sc} = 33.3$ mA/cm²
$V_{oc} = 687$ mV
FF = 77.3%
η = 17.7%
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5. Resources
Mille-Feuille concept

Objective: very thin (<40 µm) high quality c-Si films from reusable c-Si substrates.

M. Garín et al. presented at 28th EUPVSEC, Paris (2013)
State of the art.
Empty-space-in-silicon (ESS) technique

Process and Manufacturing Engineering Center, Toshiba Corp., Japan
The fine art of etching pores in c-Si
Initial pore profile

\[ \phi_w \]

\[ \phi_n \]

\[ a = 2 \, \mu m \]
Several free standing c-Si layers
Summary of mille-feuille characteristics

Monocrystalline Roughness:
- Ra: 0.11 µm
- Rq: 0.14 µm
- Rt: 1.05 µm

Thickness
- <= 6.5 µm
- Up to 35 µm with voids inside
- Up to 10 layers
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Resources: clean room

- Diffusion and oxidation furnaces
- PECVD(a-Si, a-SiCx, a-SiN, SiO₂)
- Thermal evaporation + e-gun
- 2 RF Sputtering reactors
- Lithography 2 μm
- 1064 nm Nd-YAG laser
Resources: device characterization lab

- Electrical characterization (I-V-T, C-V, solar simulator, $\tau_{\text{eff}}(\Delta n)$, etc.)
- Optical characterization (spectrophotometer, EQE, etc.)
- Solar simulator.
- Cryostat.
Resources: nano-scale characterization

Centre recerca en nano-enginyeria (CrNE).
- Atomic Force Microscopes
- Mechanical Profiler
- Optical Surface Profiler
- SEM/FIB
- XPS
Part of PV group at UPC
“Cost-effective technologies for crystalline silicon (c-Si) solar cells”

Dr. Isidro Martín
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