Photovoltaic and Photoelectrochemical Solar Cells

Dr. Katarzyna Skorupska
silicon dioxide of either quartzite gravel or crushed quartz—are first placed into an electric arc furnace, where a carbon arc is applied to release the oxygen. The products are carbon dioxide and molten silicon (1% impurities).

\[2 \text{Si} + 6 \text{HCl} \rightarrow 2 \text{HSiCl}_3 + 2 \text{H}_2,\]

Silicon tetrachloride (SiCl₄) and trichlorosilane (HSiCl₃) are intermediates in the production of ultrapure silicon in the semiconductor industry. Chlorosilanes obtained from crude silicon are purified by fractional distillation techniques and then reduced with hydrogen to give silicon of 99.999999999% purity.
Sand to silicon wafer

Sand (SiO₂) Quartzite → Metallurgical grade Si ($2/kg, 95-98% pure) → SiHCl₃ ($20/kg) → Polished Si wafer ($1300/kg) → Pure Si crystal ($400/kg) → Electronic grade Si (poly-Si) (> $80/kg)

Source: http://www.fullman.com/semiconductors/semiconductors.html

EE 6322 Semiconductor Processing Technology, Dr. J.B. Lee
Czochralski Si
Cz Si
Czochralski Si
Cz Si
Czochralski Si
Cz Si

- Seed
- Single Silicon Crystal
- Quartz Crucible
- Water Cooled Chamber
- Heat Shield
- Carbon Heater
- Graphite Crucible
- Crucible Support
- Spill Tray
- Electrode
The 99% pure silicon is purified even further using the floating zone technique. A rod of impure silicon is passed through a heated zone several times in the same direction. This procedure "drags" the impurities toward one end with each pass. At a specific point, the silicon is deemed pure, and the impure end is removed.
FLOATING ZONE PROCESS

CZOCHRALSKI GROWTH APPARATUS

Ingot

Wafers
Solar irradiation

- Fuel
  - photosynthesis
  - artificial photosynthesis
  - photocatalysis
  - photoelectrocatalysis

- Electrical power
  - photovoltaics
  - inorganic cells
  - organic cells
  - photoelectrochemical cells
  - hybrid systems

- Thermal energy
  - heat
  - electricity
Photovoltaic Cells
Optical Energy converted into Electrical Energy

Electrochemical Photovoltaic Cells
Optical Energy converted into Electrical Energy

Photoelectrosynthetic Cells
Optical energy converted into Chemical Energy

Schottky type cells: semiconductor and metal electrodes

p/n photo electrolysis cells: p-type semiconductor and n-type semiconductor

Photoelectrocatalytic cell:
  p-type semiconductor : electrolyte – H₂
  n-type semiconductor : electrolyte – O₂
**Crystalline Silicon Solar Cells**

**Design requirements**

High-efficiency crystalline solar cells require three basic elements

1. The silicon substrate must be high quality with a long carrier lifetime.
2. The cell should have low surface reflection with a good light-trapping capability.
3. Emitter design should be able to collect all light-generated carriers and good metal contacts for low series resistance.

**Manufacturing steps**

1. Silicon purification
2. Crystal growth and wafering
3. Cell processing
4. Cell encapsulation
Basic solar cell design
Crystalline Silicon Solar Cells

1954 Bell Labs., Chapin, Fuller, Pearson

6%

n-Si

p-Si

Space cell 10-12%

Violet cell 13.5%

p-Si 10 \( \Omega \text{cm} \)

n-Si 40 \( \Omega \text{cm} \), 50\( \mu \text{m} \)

AR - silicon monoxide

BSF (back surface field)

n-Si 2 \( \Omega \text{cm} \), 0.25\( \mu \text{m} \)

AR - TiO\(_2\), Ta\(_2\)O\(_5\)

Violet cell 13.5%

p-Si 10 \( \Omega \text{cm} \)

BSF (back surface field)
MINP (metal isolator N-P junction cell) 18%
- SiO₂ passivation surface underneath contact
- Current tunnel through the thin oxide
- Top contact Ti/Pd/Ag
- Rear contact Al (n⁺/p/p⁺)

PESC (Passivated Emitter Solar Cell) 20%
- No oxide underneath contact
- Contact width is reduced by laser microgrooving
PERC
Passivated Emitter and Rear Cell 20%

PERL
Passivated Emitter, Rear Locally Diffused Cell 24%
- Passivating oxide layer on top and bottom with small area contacts passivated by local heavy diffusion
**Back surface field (BSF)** - formation of the “high-low” p⁺-p junction at the back at the back of the cell. Mainly by aluminum evaporation.
Reduction of recombination velocity along p⁺-p interface by suppression of the minority-carrier concentration near the rear contact.

**Passivated Emitter Rear Locally-diffused (PERL Cell)** -
- Texture on the top surface (inverted pyramids)
  * reduction of reflection
  * photons travel obliquely across the cell
    – light is adsorbed closer to the surface
- Rear contact is separated from the silicon by intervening oxide layer.
  * much better rear reflectance
- Thin layer of thermally grow oxide
  * reduction of interface trap densities
  * surface passivation - low surface recombination rate
  * contact to n-type Si by slots
  * contact to p-type Si by holes
  * regions immediately under the contacts are heavily doped to suppress minority-carrier concentration (recombination rates)
- DLAR (double-layer antireflection) TiO₂ followed by Al₂O₃

PERL cells are used as advanced space cells and in solar-car
Spectral improvement
\( I - I_0 \alpha \)
\[
\frac{I}{I_0} = e^{-\alpha x} 
\]
\[
\frac{I}{I_0} = \frac{1}{e} \quad \text{for} \quad x\alpha = 1 
\]

For \( \alpha_1 = 10^1 \text{cm}^{-1} \)

\[
x = \frac{1}{\alpha} = \frac{1}{10^1} = 0.1\text{cm} = 0.1 \cdot 10^{-2} \text{m} = 0.001\text{m} = 100\mu\text{m}
\]

For \( \alpha_2 = 10^3 \text{cm}^{-1} \)

\[
x = \frac{1}{\alpha} = \frac{1}{10^3} = 0.001\text{cm} = 0.00001\text{m} = 10\mu\text{m}
\]

For \( \alpha_3 = 10^5 \text{cm}^{-1} \)

\[
x = \frac{1}{x} = \frac{1}{10^5} = 0.00001\text{cm} = 0.0000001\text{m} = 0.1\mu\text{m}
\]

<table>
<thead>
<tr>
<th>( \alpha \text{ cm}^{-1} )</th>
<th>10^1</th>
<th>10^3</th>
<th>10^5</th>
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<tbody>
<tr>
<td>( x \text{ \mu m} )</td>
<td>100</td>
<td>10</td>
<td>0.1</td>
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</table>

For increase of photon energy values of penetration depth decrease.
For lower photon energy, value of penetration depth is higher - electron-hole pairs are created deeper in material.

For higher photon energy, value of penetration depth is smaller - electron-hole pairs are created closer to the surface.
Quantum yield – how many electrons are created by one photon

W = 0.1 µm

L = 100 µm
Consider schematical spectral response: what are the spatial contributions to the light-induced current $j_L$?

Spatial contributions:

$x_\alpha$ large: carriers from neutral region of device (1)

$x_\alpha$ medium range: carriers from neutral region and space charge layer (2)

$x_\alpha$ small: carriers from surface-near region (n⁺-layer) (3)
Spectral response- number of carriers collected per incident photon at each wave length. 

dead internal spectral response for a semiconductor with energy gap $E_g$: 
for $h\nu < E_g$ equals 0 and for $h\nu > E_g$ equals unity.

At low photon energies, most carriers are generated in the base region because of the low coefficient in Si.

As photon energy increases above 2.5eV, the front region takes over.

Above 3.5eV, $\alpha$ becomes larger than $10^6$ cm$^{-1}$, and the spectral response derives entirely from front region.

Departure from the ideal response
- recombination of carriers

To increase the spectral response:
- increase the diffusion length
- decrease recombination velocity for electrons and holes
Back surface field

The n⁺ - p - p⁺ junction before contact:
(exercise-draw the junction after contact formation.

The construction of E(x) begins with the already formed n⁺-p junction.
Spectral improvement cont’d

The Fermi level of the (highest doped) n⁺ part dominates; after contact formation, its energetic position defines mostly $E_F^C$:

The BSF reduces the back surface recombination velocity to ~10cm/s
The reflectivity of Si for normal incidence is 34% at 1100 nm (1.12 eV) and rises to 54% at 400 nm. Proper single layer AR coatings can reduce $R \sim 10\%$ in this wavelength range. With the pyramidal NR coating, reflectivity drops to $\sim 3\%$

Advantages:
- reflectivity drops
- more effective absorption due to inclined light paths in Si
- more charge carriers generated in depletion region
- long wavelength light is absorbed more efficiently
The anisotropy of silicon etching with crystal orientation: surface atomic arrangement and:
top view of (111) and (001) surfaces

The etching procedure:
Chemical etching of Si in alkaline solution (NaOH, KOH)

\[ \text{Si}_5 (\text{Si-H-H}) + 2\text{H}_2\text{O} \rightarrow \text{H}_2\text{Si(OH)}_2 (+2\text{H attached to underlying lattice atoms}) \]

\[ \text{H}_2\text{Si(OH)}_2 + 2\text{H}_2\text{O} \rightarrow \text{Si(OH)}_4 + 2\text{H}_2 \]

Etching is anisotropic with crystal orientation
Terrace dissolution
Solar cell improvements

Spectral sensitivity of original cell and of so-called violet cell, where part of the n⁺ layer has been removed by etching

The etching procedure:
Chemical etching of Si in alkaline solution (NaOH, KOH)

\[ \text{Si}_5 (=\text{Si-H-H}) + 2\text{H}_2\text{O} \rightarrow \text{H}_2\text{Si(OH)}_2 (+2\text{H attached to underlying lattice atoms}) \]

\[ \text{H}_2\text{Si(OH)}_2 + 2\text{H}_2\text{O} \rightarrow \text{Si(OH)}_4 + 2\text{H}_2 \]

Etching is anisotropic with crystal orientation
Improvement of spectral behaviour

**Blue sensitivity:** etching of n⁺ front layer

**Red sensitivity:** back surface field

BSF: inhibiting the loss of excess electrons near the back contact: built-in electric field that repels electrons

Overcoming the tendency of minority carriers to recombine at the back contact: introducing p⁺ doping.
Point contact solar cells

Solar cell concept for concentrator applications; here, the pn junction is non-planar; instead, spatially arranged small p⁺ and n⁺ regions collect the respective carriers:

Light-generated electron hole pairs first diffuse to their respective contacts in the slightly n-type high-purity float zone Si; they are collected at n⁺ and p⁺ contacts, respectively.

Note: (i) contact spacing influences cell efficiency
(ii) around contacts, space charge regions exist
(iii) explain why electrons migrate to n⁺ and holes to p⁺ regions.
Charge collection in point contact solar cells

The path of light-generated excess carriers:

FZ n-Si
ance and vertical protrusion relative to minority carrier diffusion length
Approaches towards Stable Operation

Chemical passivation:

surface termination
- H-terminated Si surface
- Methyl terminated Si surface
Stabilization by bandstructure:

intrametallic d-d transitions

stabilization by energy band structure properties; this has been found in transition metal materials where the upper $E_{VB}$ and the bottom $E_{CB}$ are composed predominantly of metallic d-states.

Photonic absorption results, after excess carrier thermalization, in predominantly intrametallic electron-hole pairs near the surface. Thus, the metal-chalcogen/oxide bond remains largely unaffected, which suppresses photocorrosion;
Kinetic / thermodynamic stabilization:
- redox reaction (1)
- recombination reaction (2, 2a)
- surface recombination (4)
Photoexited charges can be used by:
- Photoelectrocatalytic process
- Corrosion of photoelectrode

\[
\text{Si} + 2\text{H}_2\text{O} + 4h^+ \rightarrow \text{SiO}_2 + 4\text{H}^+ \quad \text{ELECTRODE CORROSION}
\]

\[
2\text{H}_2\text{O} + 4h^+ \rightarrow \text{O}_2 + 4\text{H}^+ \quad \text{DESIRED PROCESS}
\]
Decomposition of SC thermodynamic

Decomposition potentials

\[ nE_{decomp}^c = \frac{\Delta G_1}{zF} \quad \text{for reduction of semiconductor} \]

\[ pE_{decomp}^c = \frac{\Delta G_2}{zF} \quad \text{for oxidation of semiconductor} \]

F – Faraday constant
\( \Delta G \) – known change in free Gibbs energy for each reaction
favorable decomposition
stable against cathodic reaction
stable against anodic reaction
In flat band situation by introducing into electrolyte a redox couple
- below \( nE_{\text{decomp}} \)
- above \( pE_{\text{decomp}} \)

Applying an external potential in order to create depletion situation at the surface
8.5 Competition between Redox Reaction and Anodic Dissolution

\[
\begin{align*}
\text{SnO}_2 + 4\text{HCl} \cdot \text{aq} & \rightarrow \text{SnCl}_4 \cdot \text{aq} + \text{O}_2 + 2\text{H}_2 \\
\text{SnO}_2 + 2\text{H}_2 & \rightarrow \text{Sn} + 2\text{H}_2\text{O} \\
\text{WO}_3 + \text{H}_2\text{O} & \rightarrow \text{WO}_4^{2-} + (1/2)\text{O}_2 + \text{H}_2 \\
\text{WO}_3 + 3\text{H}_2 & \rightarrow \text{W} + 3\text{H}_2\text{O} \\
\text{ZnO} + 2\text{HCl} \cdot \text{aq} & \rightarrow \text{ZnCl}_2 \cdot \text{aq} + (1/2)\text{O}_2 + \text{H}_2 \\
\text{ZnO} + \text{H}_2 & \rightarrow \text{Zn} + \text{H}_2\text{O} \\
\text{TiO}_2 + 4\text{HCl} \cdot \text{aq} & \rightarrow \text{TiCl}_4 \cdot \text{aq} + \text{O}_2 + 2\text{H}_2 \\
\text{TiO}_2 + 2\text{H}_2 & \rightarrow \text{Ti} + 2\text{H}_2\text{O} \\
\text{Cu}_2\text{O} + \text{H}_2\text{O} & \rightarrow 2\text{CuO} + \text{H}_2 \\
\text{Cu}_2\text{O} + \text{H}_2 & \rightarrow 2\text{Cu} + \text{H}_2\text{O} \\
\text{CdS} + 2\text{HCl} \cdot \text{aq} & \rightarrow \text{CdCl}_2 \cdot \text{aq} + 2\text{S} \\
\text{CdS} + \text{H}_2 & \rightarrow \text{Cd} + 2\text{H}_2\text{S} \cdot \text{aq} \\
\text{MoS}_2 + 2\text{H}_2\text{O} & \rightarrow \text{MoO}_3 + 2\text{S} + 2\text{H}_2\text{O} \left( E_{\text{dec}} \right) \\
\text{MoS}_2 + 2\text{H}_2 & \rightarrow \text{Mo} + 2\text{H}_2\text{S} \cdot \text{aq} \\
\text{GaP} + 6\text{H}_2\text{O} & \rightarrow \text{Ga(OH)}_3 + 3\text{H}_3\text{PO}_3 \cdot \text{aq} + 3\text{H}_2 \\
\text{GaP} + (3/2)\text{H}_2 & \rightarrow \text{Ga} + \text{PH}_3 \\
\text{GaAs} + 5\text{H}_2\text{O} & \rightarrow \text{Ga(OH)}_3 + 3\text{H}_3\text{AsO}_3 \cdot \text{aq} + \text{eH}_2 \\
\text{GaAs} + (3/2)\text{H}_2 & \rightarrow \text{Ga} + \text{AsH}_3
\end{align*}
\]

\[ E_{\text{abs}} \]

\[ E_{\text{NHE}} \]

\[ T \]

![Diagram](Image)

**Fig. 8.15** Positions of bandedges and decomposition Fermi levels for various semiconductors. (After ref. [51])

Physical passivation: insulating films

- Inhibition of ion transfer
- Efficient carriers transfer

for instance ALD
Motivation

Silicon nanostructures integration into existing microelectronics and PV applications

Electrochemically prepared nanostructures

- Photovoltaics
  - novel solar devices
    - light coupling

Soft solution processing particularly advantageous for semiconductors (avoiding electronic defects)

High control via current, photon flux, potential, charge and solution parameters

Very high surface sensitivity

Low temperature process

Characteristic obtained features:

- sizes well below present lithography technology limits
- expansible to large areas
Si - absorber
porous oxide layer - corrosive protection, separation of absorber from solution
metal nanorods – electrical contact between absorber and electrolyte
Under illumination
- Oxide layer transparent
- Photons absorbed in Si material (charge carriers excitation)
- Minority excess carriers collected by metal nanorods (minority charge collector)
- Majority excess carriers to back contact
Concept and realization and of nanoemitter solar cell

non-planar metal semiconductor heterojunctions

photovoltaic / photoelectrocatalytic mode

solid state photovoltaic
Protocol

- H-terminated Si (100) surface

- Porous silicon dioxide layer by oscillations in NH$_4$F
  ~8-10 nm thick layer

- Deepen of pores and the interface improvement in alkaline solution

- Site selective Pt nanoislads electrodeposition
  15 nm height, 50-200 nm radius, distance between the rods 60nm – 1µm

only self-organized processes used
I. Photocurrent oscillations

II. Nanoporous oxide

III. Pore deepening

IV. Metallization

V. Photoelectrochemical solar cell
Photoactive nanocomposite structure

oscillation in NH₄F

pores deepen in NaOH

surface topography after etching in 50% HF

Schottky barrier metal electrodeposition
Photoactive nanocomposite structure

H-terminated n-Si(100)

oscillation in NH₄F

pores deepen in NaOH

Pt nanoparticle electrodeposition
Si
SiO₂
Si
SiO₂
Si
Porous SiO₂ nanostructure

\[
\text{Si} + 2\text{H}_2\text{O} + 4\text{h}^+ \rightarrow \text{SiO}_2 + 4\text{H}^+
\]

\[
\text{SiO}_2 + 6\text{HF} \rightarrow \text{SiF}_6^{2-} + 2\text{H}^+ + 2\text{H}_2\text{O}
\]

\[
\text{SiO}_2 + 3\text{HF}_2^- \rightarrow \text{SiF}_6^{2-} + \text{H}_2\text{O} + \text{OH}^-
\]

lattice mismatch

\[V_{\text{SiO}_2} > V_{\text{Si}}\]
Typical photocurrent oscillation and the oxidic coverage measured by Fourier transformation infrared spectroscopy.
SEM images of SiO₂ surface after interrupting oscillation at:

- increasing
- maximum
- decreasing

Scale: 200 nm
Pores deepen in alkaline solution in the dark

$I / \mu A cm^{-2}$

$E / V vs. SCE$

$t / s$

$E_{fb}$

chemical anodic

$$\text{H}_2 \rightarrow 2e^- + 2 \text{H}^+$$

$$\text{H}_2 \text{O} \rightarrow 2 \text{H}^+ + 4\text{e}^- + 2 \text{OH}^-$$

anodic chemical
n-Si surface

1. porous SiO$_2$ mask creation
2. Si etching in alkaline solution
3. Pt electrodeposition

1. porous SiO$_2$ mask creation
2. Si etching in alkaline solution
3. Pt electrodeposition
4. SiO$_2$ mask etching in HF
Pt nanoparticle electrodeposition

![Graph showing current density (I) vs. potential (E)]

- Current density (I) in mA cm$^{-2}$
- Potential (E) vs. SCE
- Time (t) in seconds

![Images of Pt nanoparticles at 1µm and 200 nm scales]
Platinum detection

EDX

XPS
Pt 4f

counts / a.u.

$E_B / \text{eV}$

80 75 70 65
Best device performance for overlapped semispherical space charge layers around the Si – Pt contacts

Distance between nano-dimensioned emitters

\[ X_{\text{dis}} \leq \sqrt{2} \left( L_{e,h} + r + W \right) \]

If is fulfilled, all light-generated excess minority carriers will be collected thus allowing the preparation of efficient solar cells with nanoemitter front contacts

for Si \( L_{e,h} > 100 \ \mu \text{m} \)

The minority carriers generated close to the back contact can be collected if the inequality:

\[ Z_{\text{thickness}} = Y_{\text{depth}} + W_s + \frac{L_{h,e}}{2} \]
Electrochemical solar cell efficiency

11.2 %

\[ \eta = \frac{P_{\text{output}}}{P_{\text{input}}} \]

\[ \eta = \frac{i_{\text{mp}} V_{\text{pm}}}{i_{\text{sc}} V_{\text{OC}}} \]

\[ \eta = \frac{i_{\text{sc}} V_{\text{OC}} \cdot i_{\text{mp}} V_{\text{mp}}}{I_{\text{light}}} \]

\[ \eta = \frac{i_{\text{mp}} V_{\text{mp}}}{I_{\text{light}}} \]

2M HI, 50 mM I₂
illumination 100 mWcm⁻²

Patent:
M. Aggour, H.J. Lewerenz, K. Skorupska, Verfahren zur Herstellung eines photoaktiven Schichtenverbunds, photoaktiver Schichtenverbund und Anwendung DE: 102008004340.0, 09.01.08
Photovoltaic Photoelectrochemical Solar Cell

- Stability approach: nanoporous passive film

Acidic iodine/iodide electrolyte

\[
\text{Photocurrent density/mA/cm}^2
\]

- Pore deepening
- Without alkaline treatment
- Dark current

\[
\text{potential/V(SCE)} \quad E_{\text{r.o.}}
\]

\[
\text{After alkaline treatment}
\]

\[
\eta = 11.2\%
\]
\[
J_{sc} = 34\text{mA/cm}^2
\]
\[
V_{oc} = 0.5\text{V}
\]
\[
ff = 0.65
\]

\[
\text{Photocurrent Density mA/cm}^2
\]

\[
\text{Potential V/SCE}
\]
Existing interfaces:

i. Si : SiO$_2$

ii. Pt : SiO$_2$

iii. Pt : Si

iv. Pt : electrolyte

v. SiO$_2$ : electrolyte

two interfaces between electrolyte and solid state device

i. Pt : electrolyte

ii. SiO$_2$ : electrolyte
Contact formation
- Pt negatively charged
- Si negatively charged in contact with electrolyte

a), b) Si/SiO₂/Pt contact formation
c) Equilibrium in I⁻/I₃⁻ electrolyte

CPD (1.4eV) split between band banding (0.8eV) and band edge shift (0.6eV)
inner Helmholtz plane (IHP) specifically adsorbed I\(^-\) ions on the platinum surface create the.

outer Helmholtz plane (OHP) consists of hydronium ions.

The minority charge carrier (hole) is collected by the platinum nanoemitter and transferred to the electrical double layer, where can take a part in oxidation of I\(^-\) to I\(^{-3}\).

Si pores cover with thin oxide layer -reduction of recombination
Energy band diagram for
(a) situation before contact formation,
(b) after contact formation between Pt
(c) at the flat band potential (n-Si/SiO₂, and for device in the I⁻/I₃⁻ electrolyte)
(d) in the OCP
(e) at +0.28 V vs. SCE.

n-Si
OCP (-0.28V vs. SCE) depletion
-0.32V vs. SCE flat band situation
0.28 V vs. SCE (I⁻/I₃⁻) inversion
\[ I^- + 2e^- \leftrightarrow 3I^- \quad E_{\text{redox}}^0 = 0.3V \text{ vs. SCE} \]

i. n-Si depletion
ii. excess carriers under illumination
iii. minority carrier collected by Pt
iv. oxidation in solution \( 3I^- + 2h^+ \rightarrow I_3^- \)
v. counter electrode delivers \( e^- \) for reduction of \( I_3^- \)
The electrochemical solar cell performance in 50 mM I2, 2.5 M KI. The solid line represents the first scan, dashed line the 50th scan and dashed-dotted line the 100th scan.

The nanoemitter solar cell after operation in the iodine/iodide electrolyte.
p-Si based device for H$_2$ evolution
Previous work: Photoelectrocatalysis with p-Si/SiO$_2$/Pt-H$_2$/H$^+$/C
p-Si (100)
oscillation in NH4F

120 nm size
10-15 nm length

SEM image of porous oxide matrix on Si (100)

\[
n - \text{Si} + 4h_{VB}^+ (h \nu) + 2H_2O \Rightarrow SiO_2 + 4H_{aq}^+ \\
p - \text{Si} + 4h_{VB}^+ (V_a) + 2H_2O \Rightarrow SiO_2 + 4H_{aq}^+ \\
SiO_2 + 6HF \Rightarrow SiF_6^{2-} + 2H_{aq}^+ + 2H_2O \\
SiO_2 + 3HF_2^- \Rightarrow SiF_6^{2-} + H_2O + OH_{aq}^- 
\]
Energy scheme for the photoelectrodeposition of Pt into the nanoporous silicon oxide matrix imaged; 
\[ \Delta E_{\text{HH}} \]: energy drop in the Helmholtz layer due to surface states (shaded grey);
\[ eV_a \]: applied voltage;
\[ eV_{fb} \]: flatband potential before biasing the sample; 
the dashed downwards oriented arrow at the Pt deposition potential level indicates that the actual level is located at a more anodic potential.

deposition protocol, solution 1mM \( \text{PtCl}_6^{2-} \), 0.1M \( \text{K}_2\text{SO}_4 \), pH 3.8, light intensity 130mWcm\(^{-2} \), W-I lamp;

SEM image after Pt deposition

15 nm until 250 nm pores

SEM image after Pt deposition
Photoeffect on p-Si

H^+/H_2 / Pt SiO_2 / p-Si / GaIn

p Si(100) in 0.05M H_2SO_4

light intensity 10 mWcm^2
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<th>Characteristic</th>
<th>CZ</th>
<th>FZ</th>
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<tr>
<td>Growth Speed (mm/min)</td>
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<tr>
<td>Dislocation-Free?</td>
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<td>Yes</td>
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<td>Crucible?</td>
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<tr>
<td>Consumable Material Cost</td>
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<td>Carbon Content (atoms/cm³)</td>
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<td>Metallic Impurity Content</td>
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