USE OF LOW-ENERGY HYDROGEN ION IMPLANTS IN HIGH-EFFICIENCY CRYSTALLINE-SILICON SOLAR CELLS

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Basic Effects of Low-Energy H⁺ Implants

A. BORON NEUTRALIZATION
B. EFFECT ON ELECTRICALLY ACTIVE METALLIC IMPURITIES
C. PASSIVATION OF DANGLING BONDS
D. DEEP PERMEATION
E. HYDROGEN CAUSED DAMAGE - SYNERGISTIC EFFECTS

Effects of Low Energy H⁺ Implants on Solar Cell Behavior

A. EFFECT ON BASE
B. EFFECT ON SPACE CHARGE LAYER
C. EFFECT ON EMITTER
Hole Concentration Profiles (Moderately Doped p-type Si)

0.4 KeV H⁺

19
17
15
13

Log P (cm⁻³)

Depth (μm)

1-10 Ω-cm

40-70 Ω-cm

Spreading resistance plots showing the hole concentration in moderately doped (10¹⁵ cm⁻³ and 2x10¹⁴ cm⁻³) p-type Si samples after exposing them to 0.4 KeV H⁺ ions for 1 minute. The incident fluence of H ions was 10¹⁸ cm⁻².
Hole Concentration Profiles (B-doped p-type Si)

Hole concentration in H-ion-bombarded p-Si doped with $2 \times 10^{16}$ cm$^{-3}$ boron atoms after annealing for 1 hr at the temperature shown. Note that a 190 °C heat treatment anneals out all the compensating defects at the surface.

Deep Level Transient Spectra (Cr-doped p-type Si)

Curves showing the DLTS spectra obtained from Schottky-diodes made on Cr doped p-Si, as a function of processing: a) no treatment. b) 300 °C 1 hour anneal in an inert ambient. c) 0.4KeV H$^+$ implant for 5 minutes. Note that although the concentration of the Cr levels decreases after both heat treatment and after H$^+$ bombardment, the reduction is much more pronounced in the latter case.
Deep Level Transient Spectra (Ti-doped p-type Si)

Curves showing the DLTS spectra obtained from Schottky-diodes made on Ti-doped p-Si, as a function of processing: a) no treatment, b) 300 °C hour anneal in an inert ambient, c) 0.8Kev H⁺ implant for 5 minutes. Note that the concentration of the Ti levels is insensitive to these processes.

Data from DLTS Spectra Establish that H⁺ Low-Energy Implants:

A. DEFINITELY DO NOT AFFECT ALL METALLIC DEEP LEVELS.
B. ONLY AFFECT THE LEVELS OF FAST DIFFUSERS.
C. PASSIVATION OF FAST DIFFUSERS? ENHANCED DIFFUSION OF FAST DIFFUSERS (DUE TO RADIATION) AND GETTERING?

Passivation of Dangling Bonds

\[ \text{Si} - \text{Si} - \text{H} \]

\[ \text{Si} - \text{Si} \]

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Electron Beam Induced Current Sensors

EBIC scans taken on the front surface before any H implantation.

Scans taken on the front surface after implanting the device with H⁺ on the back of the wafer.
Rutherford Backscattering Spectra

Rutherford backscattering data in the channeling and random mode from Si samples subjected to low-energy ion-beams. Note that as the energy of the incident ions is increased, more damage is introduced at the Si surface. Further, note that H ions introduce more lattice damage than Ar ions.

Spectral Response

Danudic Wob Solar Cell 15 3
A: no H⁺
B: 0.4 keV H⁺

\[
\frac{1}{(\text{Spectral Response})} (\text{arb. units}) \quad \frac{1}{(\text{Abs. Coeff.})} (\mu m)
\]
Spectral Response

Cz-Si 75 keV, Sx10^16 cm^-2 As implant
Anneal: 550 °C 2 hrs + 500 °C 15 m + 550 °C 2 hrs
A: No H^+ After Anneal
B: 0.4 keV H^+ After Anneal

Spectral Response

Fz-Si 75 keV, Sx10^16 cm^-2 As implant
Anneal: 550 °C 2 hrs + 500 °C 15 m + 550 °C 2 hrs
A: No H^+ After Anneal
B: 0.4 keV H^+ After Anneal

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Effect of H on Space Charge Region of Solar Cells

<table>
<thead>
<tr>
<th>Device</th>
<th>( L_n ) Before ( H^+ )</th>
<th>( L_r ) After ( H^+ )</th>
<th>( I_0 ) before ( H^+ ) (A/cm(^2))</th>
<th>( I_0 ) after ( H^+ ) (A/cm(^2))</th>
<th>( I_0 ) base (A/cm(^2)) Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7 Cz-Si</td>
<td>75</td>
<td>75</td>
<td>3.096 x 10(^{-9})</td>
<td>6.47 x 10(^{-11})</td>
<td>1.1 x 10(^{-11})</td>
</tr>
<tr>
<td>S25 (Fz-Si)</td>
<td>51</td>
<td>51</td>
<td>1.667 x 10(^{-9})</td>
<td>1.57 x 10(^{-10})</td>
<td>10(^{-12})</td>
</tr>
</tbody>
</table>

Total Saturation Current and Saturation Current Component
Due to Emitter Transport for Different Devices

<table>
<thead>
<tr>
<th>Processing</th>
<th>( J_o ) (pA/cm(^2))</th>
<th>( J_o(b) ) (pA/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>#412-5C as is</td>
<td>3.78</td>
<td>1.71</td>
</tr>
<tr>
<td>#412-5C no oxide</td>
<td>7.13</td>
<td>5.06</td>
</tr>
<tr>
<td>#412-5C no oxide after ( H^+ )</td>
<td>3.90</td>
<td>1.83</td>
</tr>
</tbody>
</table>

\( J_{ob} = 2.07 \times 10^{-10} \) A/cm\(^2\)

Surface Recombination Velocity Values for Different Devices

<table>
<thead>
<tr>
<th>Model</th>
<th>( S_p ) with oxide</th>
<th>( S_p ) no oxide</th>
<th>( S_p ) no oxide with ( H^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rawston</td>
<td>1.53 x 10(^4)</td>
<td>5.66 x 10(^4)</td>
<td>1.65 x 10(^4)</td>
</tr>
</tbody>
</table>

\( J_{be} \) (with oxide) = 3.786 x 10\(^{-12}\) A/cm\(^2\).

\( J_{be} \) (without oxide) = 7.13 x 10\(^{-12}\) A/cm\(^2\).

\( J_{be} \) (no oxide + 0.4 keV \( H^+ \)) = 3.90 x 10\(^{-12}\) A/cm\(^2\).
Conclusions

A. HYDROGEN IMPLANTS ARE VERY USEFUL BECAUSE

1. CAN PASSIVATE DANGLEING SI BONDS AT BULK AND SURFACE DEFECTS.
2. CAN PENETRATE DEEPLY DOWN DISLOCATIONS AND GRAIN BOUNDARIES.
3. CAN GETTER (OR PASSIVATE) FAST DIFFUSING METALLIC IMPURITIES
   (BUT NOT SLOW DIFFUSING IMPURITIES - AT LEAST IF DOPED FROM
   THE MELT).

B. HYDROGEN IMPLANTS CAN IMPROVE CELLS THROUGH
   IMPROVEMENT OF

1. BASE
2. SPACE CHARGE LAYER
3. EMITTER (AND EMITTER SURFACE)

C. CAUTIONS

1. HYDROGEN IMPLANTS THEMSELVES CAUSE DAMAGE.
2. HYDROGEN CAUSES BORON NEUTRALIZATION (WHICH ANNEALS OUT IF
   T ≥ 180°C OR IS NOT PRESENT IF PROCESSING TEMPERATURE ≥
   150°C).