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)

Spreading resistance plots showing the hole concentration in moderately doped ($10^{15}$ cm$^{-3}$ and 2x$10^{14}$ 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 $10^{18}$ cm$^{-2}$.
Hole Concentration Profiles (B-doped p-type Si)

Hole concentration in H-ion-bombarded p-Si doped with $2 \times 10^{14}$ 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 N$^+$ implant for 5 minutes. Note that although the concentration of the Cr levels decreases after both heat treatment and after IB bombardment, the reduction is much more pronounced in the latter case.
Deep LevelTransient 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) 0.4MeV 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

= Si — Si = H

= Si — Si =
Electron Beam Induced Current Scans

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

Donohue Web Solar Cell 153
A: no H⁺
B: 0.4 keV H⁺
Spectral Response

Cz-Si 75 keV, 5x10^{15} cm^{-2} As implant

Anneal: 550 °C 2 hrs + 900 °C 15 min + 550 °C 2 hrs

A: No H⁺ After Anneal
B: 0.4 keV H⁺ After Anneal

Spectral Response

Fz-Si 75 keV, 5x10^{15} cm^{-2} As implant

Anneal: 550 °C 2 hrs + 900 °C 15 min + 550 °C 2 hrs

A: No H⁺ After Anneal
B: 0.4 keV H⁺ After Anneal
Effect of H on Space Charge Region of Solar Cells

<table>
<thead>
<tr>
<th>Device</th>
<th>$L_n$ Before $H^+$</th>
<th>$L_n$ After $H^+$</th>
<th>$I_o$ before $H^+$ (A/cm²)</th>
<th>$I_o$ after $H^+$ (A/cm²)</th>
<th>$I_o$ base theoretical (A/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7 Cz-Si</td>
<td>75</td>
<td>75</td>
<td>$3.096 \times 10^{-9}$</td>
<td>$6.47 \times 10^{-11}$</td>
<td>$1.1 \times 10^{-11}$</td>
</tr>
<tr>
<td>S25 (Fz-Si)</td>
<td>51</td>
<td>51</td>
<td>$1.667 \times 10^{-9}$</td>
<td>$1.57 \times 10^{-10}$</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>$J_o$ (A/cm²)</th>
<th>$J_o$ $J_a$ (A/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4412-5C as is</td>
<td>3.78</td>
<td>1.71</td>
</tr>
<tr>
<td>4412-5C no oxide</td>
<td>7.13</td>
<td>5.06</td>
</tr>
<tr>
<td>4412-5C no oxide after $H^+$</td>
<td>3.90</td>
<td>1.83</td>
</tr>
</tbody>
</table>

$J_{ob} = 2.07 \times 10^{-10}$ A.cm²

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>Roulston</td>
<td>$1.53 \times 10^4$</td>
<td>$5.66 \times 10^4$</td>
<td>$1.65 \times 10^4$</td>
</tr>
</tbody>
</table>

$J_{be}$ (with oxide) = $3.786 \times 10^{-12}$ A.cm².

$J_{be}$ (without oxide) = $7.13 \times 10^{-12}$ A/cm².

$J_{be}$ (no oxide + 0.4 keV $H^+$) = $3.90 \times 10^{-12}$ A/cm².
Conclusions

A. HYDROGEN IMPLANTS ARE VERY USEFUL BECAUSE

1. CAN PASSIVATE DANGLING SI BONDS AT BULK AND SURFACE DEFECTS.
2. CAN PERNERATE 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
   \( T \geq 180^\circ C \)) OR IS NOT PRESENT IF PROCESSING TEMPERATURE \( \geq 
   150^\circ C \)).