Reassessment of the Recombination Parameters of Interstitial Cr and CrB pairs in Silicon

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Cr in photovoltaic silicon materials
- Transition-metal impurities such as Cr are detrimental to silicon devices.
- But such impurities are common in photovoltaic grade silicon materials.
- Cr in photovoltaic grade multicrystalline silicon wafers: \(10^{12} - 10^{13} \text{cm}^{-3}\) range.

Recombination activity of Cr
In n-Si: isolated interstitial chromium Cr
\[ E_c \]
\[ \text{Cr}_i + E_c (0.22 \pm 0.02) \text{eV} \]
\[ \text{CrB, } E_c (0.28 \pm 0.02) \text{eV} \]

In p-Si: \( \text{Cr}_i + B \rightarrow \text{CrB pairs} \)
\[ > 200 - 300^\circ \text{C} \]

Deep recombination centers
Enhance recombination & Reduce carrier lifetime

Defect parameters:
- Capture cross sections & Energy level
- Vary across orders of magnitudes in literature

Reassessment of recombination parameters
Samples: 5 n-type Cr-doped samples and 5 p-type ones. They are cut from different positions (different solidified fraction \(g\), different doping) of two Czochralski ingots.

Doping level- and injection-dependent lifetime data of both types of samples

Fit Shockley-Read-Hall (SRH) model

Recombination parameters & uncertainty range
Combined analysis of the two defects \(\rightarrow\) Reduced uncertainty and tightened range

FIG. 1. Lifetime measurements (symbols) and SRH fits (solid lines) for (a) n-type samples, (b) p-type samples in fully associated state, and (c) p-type samples directly after quenching.

Results in comparison with the literature

<table>
<thead>
<tr>
<th>(\sigma_i (\text{cm}^2))</th>
<th>(\sigma_j (\text{cm}^2))</th>
<th>(\sigma_i/\sigma_j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Cr}_i)</td>
<td>Literature ((0.73, 25)\times10^{-14})</td>
<td>((0.91, 12.5)\times10^{-14})</td>
</tr>
<tr>
<td>This work ((1.0, +0.3)\times10^{-14})</td>
<td>((0.8, -0.3, +0.2)\times10^{-14})</td>
<td>3.2 (-0.6, +0)</td>
</tr>
<tr>
<td>(\text{CrB})</td>
<td>Literature ((0.5,15)\times10^{-14})</td>
<td>((0.15,8.4)\times10^{-14})</td>
</tr>
<tr>
<td>This work ((1.6, +0.5)\times10^{-14})</td>
<td>((0.7, -0.3, +0.6)\times10^{-14})</td>
<td>5.8 (-3.4, +0.6)</td>
</tr>
</tbody>
</table>

Comparison of Cr in n- and p-type silicon

A direct experimental comparison (Fig. 2) shows \(\text{Cr}_i\text{in p-Si} > \text{(more active than) Cr}_i\text{in n-Si}\)

We also found that \(\text{CrB in p-Si} > \text{Cr}_i\text{in p-Si}\)

✓ Since dissolved chromium will exist as CrB pairs in p-Si under standard solar cell operation conditions, we can conclude that Cr has a greater negative impact on carrier lifetimes in p-type silicon than n-type silicon with similar doping levels.

FIG. 2. Lifetime measurements (symbols) for samples n-type (\(g=0.32\)) and p-type (\(g=0.63\)). The two samples have similar doping levels and Cr concentration.