SUPPLEMENTARY INFORMATION FOR: MAXIMIZING TANDEM SOLAR CELL POWER EXTRACTION USING A THREE-TERMINAL DESIGN

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I. DETAILS OF ELECTRICAL DEVICE SIMULATION

The geometry of the simulated device consists of an n-type Si substrate with interdigitated back polysilicon on oxide (POLO) contacts consisting of an interfacial SiO₂ and heavily doped poly-Si of both polarities. The poly-Si regions are contacted with Al through smaller area openings within a dielectric layer (shown in Fig. 2a of main text). The entire front surface of the cell was coated with an n-type POLO contact and defined as a uniform contact to simulate the performance of a transparent conductive adhesive (TCA) layer. For simplicity, the poly-Si layers are electrically defined as separate c-Si regions with different doping densities, and any photogeneration in these layers is ignored.

The passivated contact structure was modeled for n-type contacts using a thin tunneling SiO₂ layer, as has been previously demonstrated, and by specifying the electron and hole recombination velocities at the c-Si/poly-Si interface. Having a well-passivated interface at the front of the cell is critical to achieve high efficiency devices. Two terminal (2T) simulations of a similar device without any front passivation (assuming ohmic contact), resulted in severely degraded cell performance in both front-back (FB) and IBC mode. In POLO experimental devices, dopants from the poly-Si diffuse into the bulk wafer through the oxide passivation layer. This phenomena was simulated using Gaussian doping profiles to approximate the maximum concentration and depth of indiffusion. Table I lists the geometric and doping parameters used to simulate the Si device.

To accurately model Si solar cell behavior, physical models were chosen based on the recommendations of Altermatt and prior simulation of passivated contact Si devices. Recombination at all semiconductor/metal contacts was defined by specifying electron and hole recombination velocities. Recombination at semiconductor/dielectric surfaces was accounted for using a surface Shockley-Read-Hall model. The models and model inputs used for the simulation are listed in Table II.

To enable comparison of different operation modes, simulations in 2T and 4T mode were carried out for comparison to the 3T device. Although cells with different numbers of terminals would be optimized slightly differently with regards to doping profiles, contact geometry, etc., in this work simulations of different cell configurations all used the same device geometry and doping to enable direct comparison of different operation modes. In practice, a 2T Si solar cell with FB contacts can be made with a blanket emitter back contact and not interdigitated back contacts. Simulations comparing a device with a full-back emitter and an optimized selective emitter such as that used in a POLO device only showed a minor difference in device performance. 4T devices were simulated using the IBC contacts of the Si cell, because the TCA interconnection that is optically simulated does not enable the lateral current extraction that is needed. Note that for a 4T tandem device, an additional grid would be needed to extract current from the back of the top cell, that would add additional shading loss to the bottom cell, so the 4T results presented for comparison are potentially a slight over-estimate of the achievable 4T tandem performance.

II. DETAILS OF OPTICAL DEVICE SIMULATIONS

Vastly different length scales are needed to capture the electrical and optical performance of an IBC device, so it common practice in the TCAD modeling of solar cells to first calculate an optical generation profile and then use this profile to solve the device physics of the cell. This enables the optical generation profile to guide the meshing of the device area, so that regions of high optical absorption are meshed more densely, which enhances the efficiency of convergence of the device physics model. All optical generation profiles were
TABLE III. Device parameters for Si cell

<table>
<thead>
<tr>
<th>Air Mass</th>
<th>APE (eV)</th>
<th>Total Power (mW cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM 1</td>
<td>1.84</td>
<td>93.09</td>
</tr>
<tr>
<td>AM 1.5</td>
<td>1.80</td>
<td>100.45</td>
</tr>
<tr>
<td>AM 2</td>
<td>1.78</td>
<td>86.81</td>
</tr>
<tr>
<td>AM 3</td>
<td>1.74</td>
<td>67.85</td>
</tr>
<tr>
<td>AM 4</td>
<td>1.71</td>
<td>55.78</td>
</tr>
<tr>
<td>AM 5</td>
<td>1.68</td>
<td>47.32</td>
</tr>
</tbody>
</table>

The output of the TCAD simulations provides the potential and current of each contact. To accurately calculate the power and efficiency of the device, it is important to accurately define the current densities and voltages, as the raw outputs of the simulation are not scaled appropriately. Equations 1 and 2 were used to define \( V_{IBC} \) and \( V_{FB} \), which can then be used to calculate the power of the sub-circuit. The following equations summarize how the power of each sub-circuit of the 3T Si are calculated from simulation data:

\[
V_{IBC} = V_{p,back} - V_{n,back} \quad (1)
\]
\[
V_{FB} = V_{p,back} - V_{n,front} \quad (2)
\]
\[
P_{Si,IBC} = I_{IBC} \times V_{IBC} \quad (3)
\]
\[
P_{Si,FB} = I_{FB} \times V_{FB} \quad (4)
\]
\[
P_{Si,Tot} = P_{Si,IBC} + P_{Si,FB} \quad (5)
\]

The following equations summarize how the total power of the tandem devices are calculated for 2T, 3T, and 4T interconnection configurations.

\[
P_{2TT} = I_{FB,tandem} \times (V_{11IV} + V_{Si,FB}) \quad (6)
\]
\[
P_{3TT} = (I_{11IV} \times V_{11IV}) + (I_{Si,IBC} \times V_{Si,IBC}) \quad (7)
\]
\[
P_{4TT} = I_{FB,tandem} \times (V_{11IV} + V_{Si,FB}) + (I_{IBC} \times V_{IBC}) \quad (8)
\]

IV. EXPERIMENTAL 3T MEASUREMENTS

To confirm our simulation results, we have compared our modeled performance to experimental measurements of 3T POLO Si cells measured as IJ devices (i.e. without a top cell).\(^{5}\) Experiments were carried out under non-standard illumination conditions where the incident power of the light on the back of the cell was adjusted to give a short-circuit current density of 10 mA for a 1 cm\(^2\) device. Figure 2 shows that the performance in FB and IBC mode is nearly identical which supports the simulated results of the same device structure.
FIG. 2. Experimental I-V data for a 3T Si POLO cell measured in FB and IBC mode. Illumination was provided from an uncalibrated source, adjusted to give a current of 10 mA for a 1 cm² device.

V. REFERENCES