Supplemental Information

Soft Imprinted Ag Nanowire Hybrid Electrodes on Silicon Heterojunction Solar Cells

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Electrical sheet resistance *vs.* optical transmission

The tradeoff between optical transmission and sheet resistance of thick/thin ITO and six nanowire networks is shown in Fig. S1. The measured sheet resistances are also reported in Table 1. Transmission was calculated using a finite-difference time-domain (FDTD) model for both ITO and the NW networks to account for their response *in situ* within the solar cell environment, and then weighted with the AM1.5G photon density spectrum.

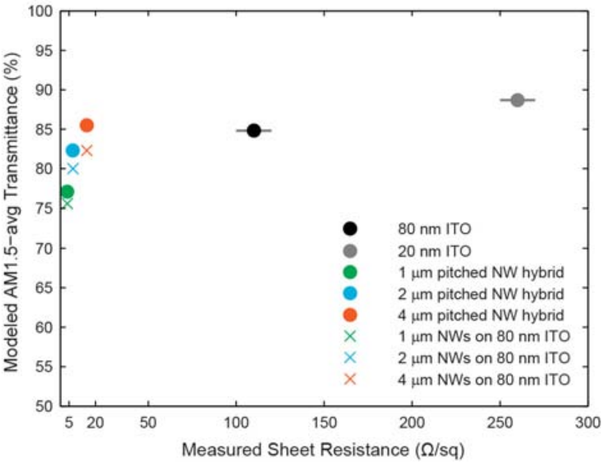

Figure S1. Transmission (AM1.5G photon density weighted) *vs.* sheet resistance. The sheet resistances were measured by 4-point probe, and are listed in Table 1. Error bars correspond to spatial variations in the sheet resistance. Since *in situ* measurements of transmission within the solar cell layers were not possible, the transmission spectra and weighted averages were calculated using the same FDTD model as Fig. 3 and Fig. 4. As in the measured devices, both reflection and absorption contribute to reduced transmission.

From Fig. S1 it is clear that the optimized 4 μm-pitched NW hybrid electrode can exceed the transparency of ITO simultaneously with a 10x reduction in sheet resistance. A similar plot for nanowire networks on glass, where both transmission and sheet resistance could both be measured, is shown in reference [1].

Optimizing finger spacing

Finger spacing significantly impacts both shading and electrical losses (Fig. S2). This can be clearly demonstrated using PatOpt [2], which is a finite element solver, to model the electrical properties of crystalline silicon solar cells with so-called H-pattern metallization (narrow fingers connected by wide bus bars). Two emitter sheet resistances are shown in Fig. S2b: high R_{sheet} (100 Ω/sq) corresponding to our most conductive experimental ITO layer, and a low R_{sheet} (15

Ω/sq) corresponding to the nanowire electrode. Cells were modeled using a single diode, and a constant local generation current.

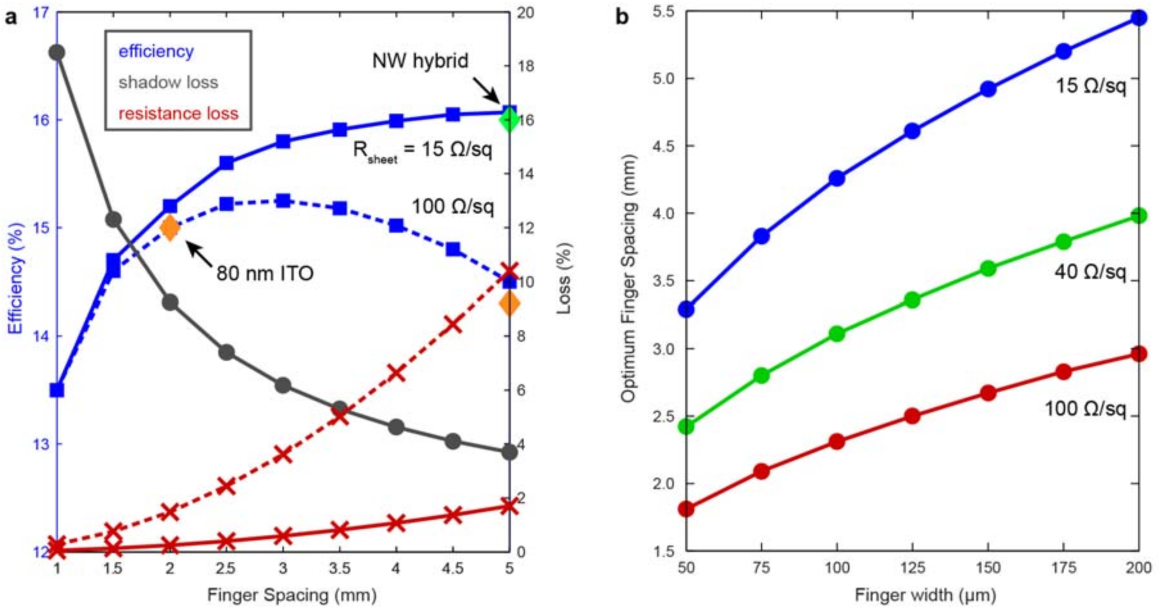

Figure S2. Modeled impact of emitter sheet resistance (R_{sheet}) on optimal finger spacing. a, Efficiency and absorption/shadowing losses as a function of finger spacing for emitters with R_{sheet} = 100 Ω/sq (dashed lines), and 15 Ω/sq (solid lines), assuming identical diode behavior and local generation current. **b,** Optimized finger spacings for three sheet resistances (15, 40, and 100 Ω/sq) and finger widths between 50 – 200 µm.

For a fixed finger width of 185 microns the shading losses are significant (Fig. S2a, grey line), leading to a maximum efficiency at a 3 mm finger spacing for the reference cell with 80 nm ITO (100 Ω/sq; dashed lines). For the high conductivity TCE (15 Ω/sq; solid lines), the efficiency continues to increase up to a 5 mm optimum finger pitch, corresponding to low resistive losses (solid red line). Along with R_{sheet}, the optimum spacing also depends on finger width (Fig. S2b). Increased finger widths lead to an increased optimized spacing.

External quantum efficiency (EQE) spectra

Local, simultaneous measurements of EQE and specular reflection were performed using an Oriel IQE 200B to verify the local impact of the nanowire electrode (Fig. S3). The spectra were measured following 10 months of atmospheric exposure, showing the robust protection offered by the SiN_x encapsulation of the Ag nanowires. These spectra were measured without white light bias.

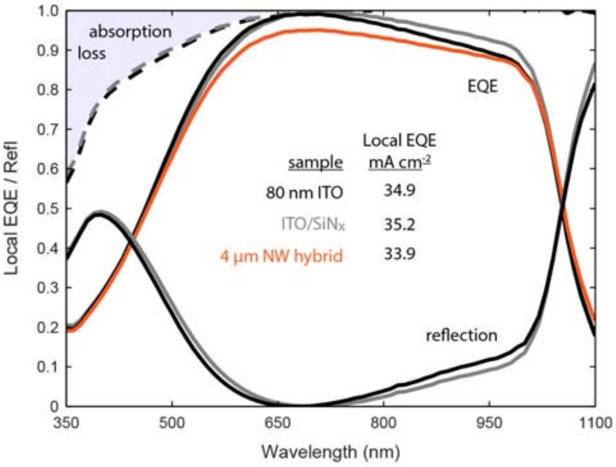

Figure S3. Measured local EQE spectra for the champion NW-hybrid and two reference cells. Reflection spectra were measured at normal incidence; for the two planar cells, the absorption loss is shown in the shaded region, and given by 1-EQE-reflection. For the hybrid design the weak off-normal scattering prevented the acquisition of a meaningful reflection spectrum simultaneously with the EQE spectrum.

The integrated local EQE shows the optical impact of the NW hybrid electrodes on cells with a range of finger widths and pitches. For the nanowire hybrid, the integrated local EQE shows a local loss of 1.0 mA cm^{-2} for the NW hybrid relative to the 80 nm ITO reference. The missing light is primarily scattered, as shown by the integrated reflection spectra in Fig. 3a, and could be further reduced by optimizing the fabricated geometry (see modeled spectra, Fig. 3b). However, the high network conductivity allows an increase in finger spacing from 2 to 5 mm, yielding a net improvement at the cell level that depends on the absolute finger widths.

Finger widths giving enhanced efficiency

Any additional local losses from the TCE layer must be compensated with a reduction in shading exceeding the local loss. The range of fingers benefiting from a given fractional loss is plotted in Fig. S4 using a geometric model: $W_{breakeven} = S_{2mm} – S_{5mm} - L_{front}$, where S is the fractional shading from 2 mm or 5 mm finger spacing and L_{front} is a constant local loss. For our experimental EQE curves, which show a front-surface loss of 3.0%, this shows we can enhance the efficiency of cells with finger widths exceeding 100 μm (5% shading losses) (Fig. S4b, orange asterisk). Refined fabrication and geometric optimization of the nanowires could reduce the relevant finger widths further.

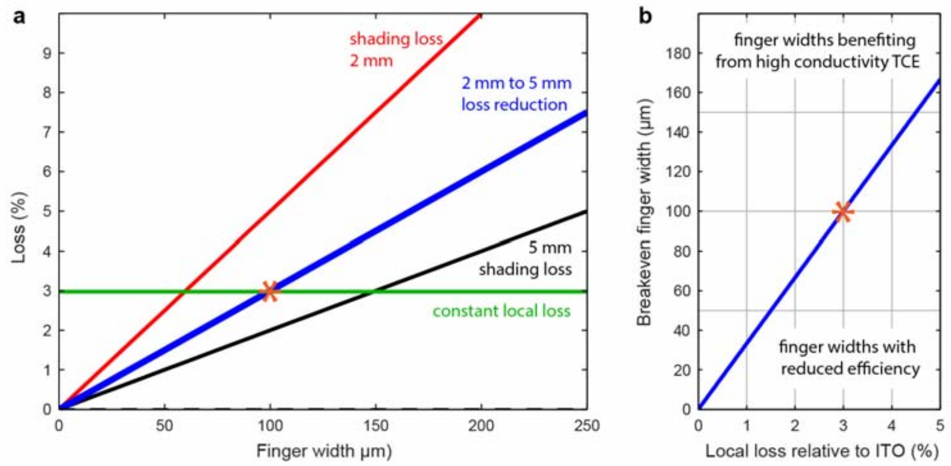

Figure S4. Range of finger widths leading to enhanced efficiency. a, geometric shading losses for 2 and 5 mm finger pitches (red and black lines), along with the improvement from replacing 2 mm fingers with 5 mm fingers (blue line). Assuming a constant local optical loss (green line), the minimum finger width where the lossy front-surface TCE still yields benefits can be found (orange asterisk). Here, the 3% local loss corresponds to the measured local loss based on the integrated EQE curves in Fig. S2. **b,** For a range of front surface loss percentages, the minimum finger widths still requiring the high-conductivity TCE can be calculated. Industry-standard fingers are 80-100 μm wide.

References

[1] J. van de Groep, D. Gupta, M.A. Verschuuren, M.M. Wienk, R.A.J. Janssen, A. Polman, Large-area soft-imprinted nanowire networks as light trapping transparent conductors, Sci. Rep., 5 (2015) 11414.
[2] PatOpt, optimising H-grid patterns with PatOpt program. Author: A.R. Burgers, ECN, the Netherlands.