Supporting Information:

Spatial Mapping of Efficiency of GaN/InGaN Nanowire Array Solar Cells using Scanning Photocurrent Microscopy

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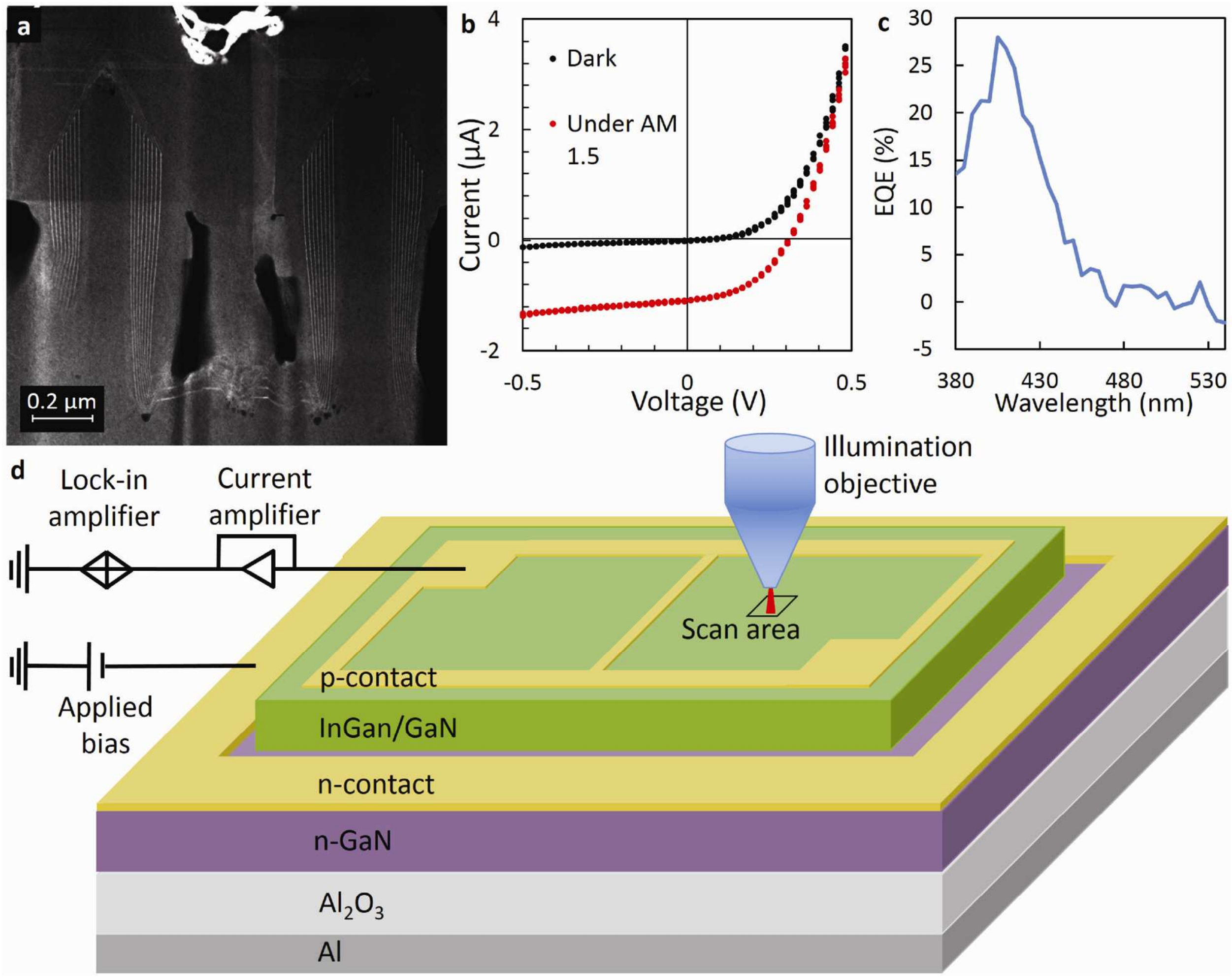
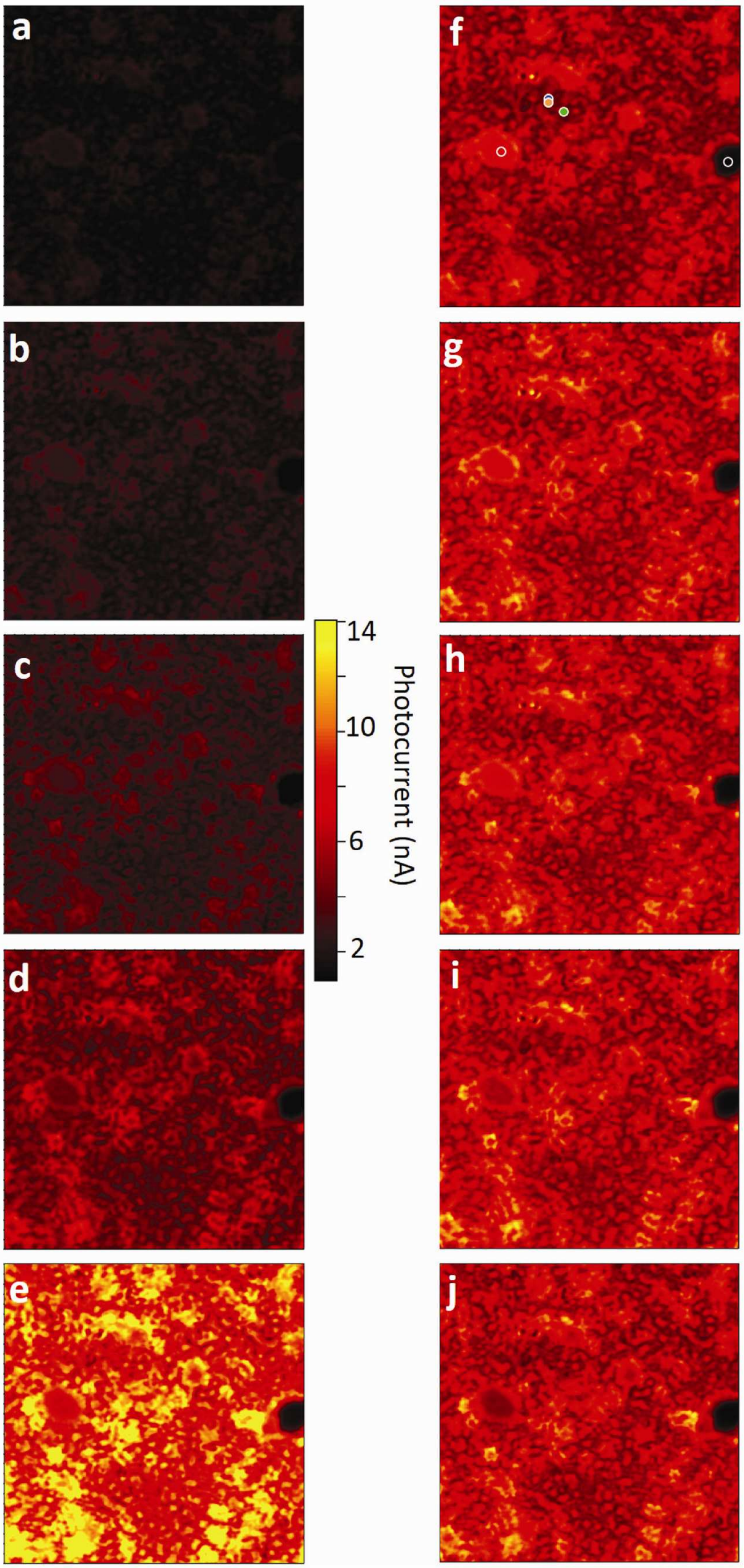


Supporting Information S1. a) ADF-STEM cross-sections of a row of hexagonally packed nanowires along the second nearest neighbor direction, revealing MQWs on the substrate between wires. b) IV curve of the device in this work in the dark and under AM 1.5 showing solar photovoltaic performance. c) Spectrally resolved External Quantum Efficiency under global illumination for the device in this work. d) Schematic of the SPCM measurement. During SPCM, a diffraction-limited laser spot from a confocal microscope is scanned across the surface of the device while the photocurrent is recorded through the contacts as a function of position. A current preamplifier and phase sensitive detection were used to measure the modulated photocurrent. Scans of 30 x 30 μm^2 were acquired using a 100x/0.9NA objective lens at powers of 25 μW or less. For illumination wavelengths of 405 nm and 500-600 nm, focused $1/e^2$ laser spot diameters are 550 nm and 680-810 nm respectively and the diffraction limited resolution is 275 nm and 340-410 nm, respectively. The SPCM scans reveal the function of individual nanowires spaced only ~500 nm apart indicating the resolution is at least 500 nm. Absorption and photocarrier generation occurs predominantly in the InGaN MQWs since photon energies are below the band gap of GaN. At each illumination position, all the photoactive regions within the Gaussian laser beam spot can contribute to the detected photocurrent. For reference, the penetration depth of 405 nm light for $In_xGa_{1-x}N$ is ~140 nm and ~70 nm for indium mole fractions of 0.1 and 0.2 respectively.[1-3]


a
b
c
d
e
f
g
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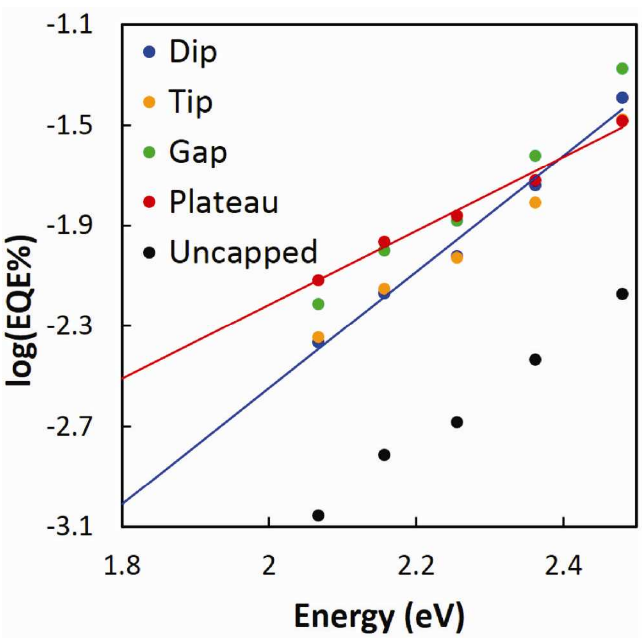
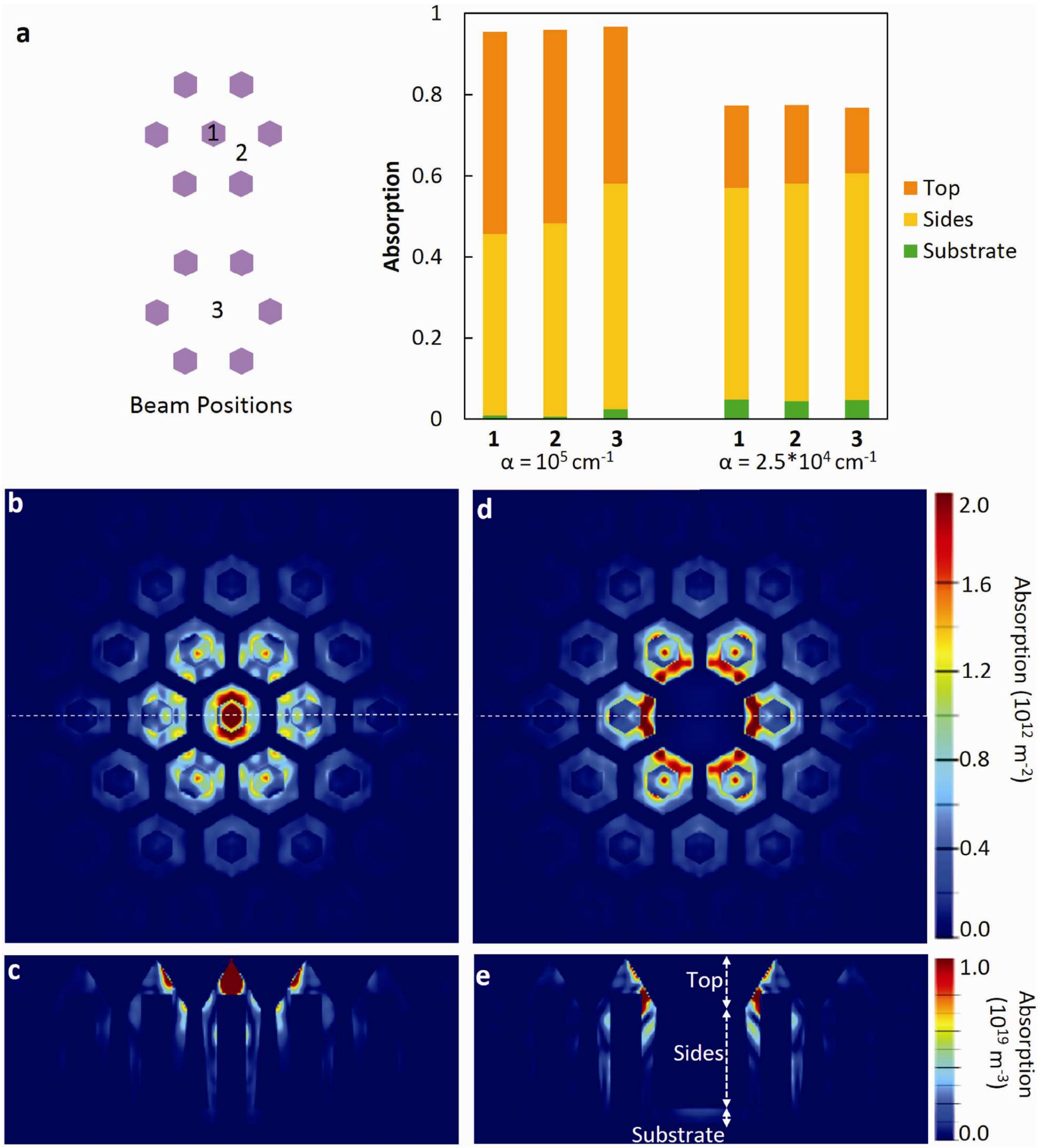
14
10
6
2
Photocurrent (nA)

Supporting Information S2. SPCM photocurrent maps were acquired at the wavelengths between 500 nm and 600 nm (S2) to identify the effective band edge. Unscaled SPCM images measured at a) 600nm, b) 575nm, c) 550nm, d) 525nm, and e) 500nm. Normalized SPCM images measured at f) 600nm, g) 575nm, h) 550nm, i) 525nm, and j) 500nm.



Supporting Information S3. The plot of log(EQE) vs. photon energy illustrates the photocurrent threshold calculation for five example locations indicated by colored dots in S2f. EQE is calculated by dividing the total number of electrons collected (from the photocurrent) by the total number of incident photons (from the incident light power). For this device, log(EQE) was observed to depend approximately linearly on photon excitation energy E_γ, so we define the photocurrent threshold energy as the intercept of a linear fit of log(EQE) versus E_γ at each position of a map.



Supporting Information S4. The FDTD model includes a flat InGaN layer of uniform thickness on the substrate between the wires, and the InGaN/GaN MQW absorber layer is modeled as a single material with a constant effective absorption coefficient. This effective absorption in the main text (Figure 3) uses a coefficient $\alpha = 2.5*10^4$ cm^{-1}, which is 25% of that of $In_{0.15}Ga_{0.85}N$ to account for GaN barrier layers that take up about 75% of the InGaN/GaN MQW absorber layer volume. We also simulated structures with a higher effective absorption coefficient $\alpha = 10^5$ cm^{-1}, as is expected in the indium-rich Top. a) For two different absorption coefficients of the absorber layer ($\alpha = 2.5*10^4$ cm^{-1} or 10^5 cm^{-1}), the absorption from FDTD simulations at 405nm was separated into Top, Sides, and Substrate components for illumination centered at the depicted beam positions. Using an absorption coefficient of 10^5 cm^{-1}, the top-view (of the center 3 by 3 μm^2 section of the simulation) is plotted in b) for beam position 1 and in d) for beam position 2. c) and e) are side-views of absorption in the plane indicated by the white dotted lines in b) and d) respectively. The arrows in e) indicate regions described in the analysis as Top, Sides, and Substrate. The model structures assume a constant absorption coefficient in the InGaN MQW layer and in a uniform InGaN layer on the substrate, between the wires. The n-GaN and p-InGaN were assumed to have a real index of 2.4 and zero imaginary index at 405 nm and the InGaN layer was assumed to have a real index of 2.54 and an imaginary index of 0.0805 or 0.322.[4] For all simulations, the 405 nm Gaussian beam was focused at a height of 0.74 μm above the GaN substrate and PML boundary conditions were used. The absorption was integrated over a circular area with a diameter of 4.4 μm centered on the beam location. Simulations were 4.9 by 4.9 μm^2 to minimize edge effects, and thus included up to the first 8 nearest neighbors. Dimensions of the simulated wires are the same as those in Figure 1a.

1. Jani, O. K. Development of Wide-Band Gap InGaN Solar Cells For High-Efficiency Photovoltaics. PhD Thesis, Georgia Institute of Technology, 2008.
2. Parker, C. A.; Roberts, J. C.; Bedair, S. M.; Reed, M. J.; Liu, S. X.; El-Masry, N. A.; Robins, L. H., Optical band gap dependence on composition and thickness of In[sub x]Ga[sub 1−x]N (0<x<0.25) grown on GaN. *Appl. Phys. Lett.* **1999,** 75, 2566-2568.
3. Schenk, H. P. D.; Leroux, M.; de Mierry, P., Luminescence and absorption in InGaN epitaxial layers and the van Roosbroeck–Shockley relation. *J. Appl. Phys.* **2000,** 88, 1525-1534.
4. Lee, T. X.; Lin, C. Y.; Ma, S. H.; Sun, C. C., Analysis of position-dependent light extraction of GaN-based LEDs. In *Opt. Express*, 2005; Vol. 13, pp 4175-4179.