

LETTERS

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A nanophotonic solar thermophotovoltaic device

Andrej Lenert1, David M. Bierman1, Youngsuk Nam1,4, Walker R. Chan2,3, Ivan Celanovic´3, Marin Soljacˇic´2,3 and Evelyn N. Wang1\*

The most common approaches to generating power from sunlight are either photovoltaic, in which sunlight directly excites electron–hole pairs in a semiconductor, or solar– thermal, in which sunlight drives a mechanical heat engine. Photovoltaic power generation is intermittent and typically only exploits a portion of the solar spectrum efﬁciently, whereas the intrinsic irreversibilities of small heat engines

the photovoltaic bandgap (*E*g) and low emittance for energies below the bandgap. To excite enough thermal modes for substantial emission above the bandgap, the emitter temperature should ideally[12](#_bookmark4) be high enough that Planck’s blackbody peak coincides

with the bandgap; in other words, by Wien’s displacement law,

*T*opt ≈ 2336 [K eV−1]· *E*

e g

make the solar–thermal approach best suited for utility-scale

power plants. There is, therefore, an increasing need for hybrid technologies for solar power generation[1,2](#_bookmark14). By converting

The high-temperature operation of the emitter poses two key chal- lenges to efﬁcient STPV power conversion: collecting sunlight to

opt

sunlight into thermal emission tuned to energies directly above

efﬁciently reach *T*e

and maintaining spectral selectivity at elevated

the photovoltaic bandgap using a hot absorber–emitter, solar

thermophotovoltaics promise to leverage the beneﬁts of both approaches: high efﬁciency, by harnessing the entire solar spectrum[3–5](#_bookmark15); scalability and compactness, because of their solid-state nature; and dispatchablility, owing to the ability to store energy using thermal or chemical means[6–8](#_bookmark18). However,

temperatures. Past STPV embodiments have relied on the intrinsic

properties of materials such as tungsten[9,10](#_bookmark19). For the absorber, one approach to effectively enhance the intrinsic solar absorptivity of materials is to use macro-cavity geometries. Because of the high aspect ratio of the cavity needed to enhance absorption, this approach typically requires high levels of optical concentration to

opt

efﬁcient collection of sunlight in the absorber and spectral

reach *T*e

(for example, 3,183 times, as used by Datas and

control in the emitter are particularly challenging at high

operating temperatures. This drawback has limited previous experimental demonstrations of this approach to conversion

Algora[9](#_bookmark19), and 4,600 times, as used by Vlasov *et al.*[10](#_bookmark20)). Such a high optical concentration in turn requires complex systems with rela- tively low optical efﬁciencies (*h*o 65%)[9](#_bookmark19). For the emitter, the

opt

≈

efﬁciencies around or below 1% (refs 9–11). Here, we report

intrinsic spectral selectivity of tungsten is poor at *T*e

because the

on a full solar thermophotovoltaic device, which, thanks to

the nanophotonic properties of the absorber–emitter surface, reaches experimental efﬁciencies of 3.2%. The device integrates a multiwalled carbon nanotube absorber and a one-dimensional Si/SiO2 photonic-crystal emitter on the same substrate, with the absorber–emitter areas optimized to

tune the energy balance of the device. Our device is planar and compact and could become a viable option for high- performance solar thermophotovoltaic energy conversion.

Because no portion of incident sunlight reaches the photovoltaic cell directly, the performance of solar thermophotovoltaics (STPVs) relies on the efﬁciency of several intermediate energy conversion steps. Optically concentrated sunlight is converted into heat in the absorber, the absorber temperature rises, heat conducts to the emitter, and the hot emitter thermally radiates towards the photo- voltaic cell, where radiation is ultimately harnessed to excite charge carriers and generate power [(Fig.](#_bookmark0) 1a). The overall efﬁciency *h*stpv can be expressed as a product of the optical efﬁciency of con-

centrating sunlight (*h*o), the thermal efﬁciency of converting and

delivering sunlight as heat to the emitter (*h*t), and the efﬁciency of generating electrical power from the thermal emission (*h*tpv):

*h*stpv = *h*o*h*t*h*tpv

The thermophotovoltaic (TPV) efﬁciency *h*tpv hinges on the

emissivity at low photon energies (,*E*g) increases with temperature, accompanying an increase in electrical resistivity[13](#_bookmark5). Ultimately, the reliance on the intrinsic spectral properties of materials for the

absorber–emitter has limited previously reported experimental STPVs to conversion efﬁciencies around 1% (refs 9–11).

To improve the performance of the absorber–emitter, research- ers have investigated the design of structured surfaces[5,6,14–21](#_bookmark17) with spectral properties approaching those of ideal STPV components (speciﬁcally, the use of photonic crystals to control the photon density of states for narrow-band selective emission[5,6,14–20](#_bookmark17)). Simulation studies using realistic nanophotonic surfaces predict STPV efﬁciencies exceeding 40% (refs 5,15,21). Although the intrin- sic material properties are sensitive to temperature, the surface structure affords a degree of spectral tunability that is tempera- ture-independent. Nevertheless, these surfaces have not yet been integrated into STPV devices operating at high enough temperatures for efﬁcient power conversion.

In our device, the spectral properties of the absorber–emitter are tailored through surface nanostructuring in a compact planar layout [(Fig.](#_bookmark0) 1a,b). The absorber–emitter module is composed of an array of multiwalled carbon nanotubes (MWNTs) as the solar absorber and

a one-dimensional Si/SiO2 photonic crystal (1D PhC) as the selective emitter. We varied the emitter-to-absorber area ratio (AR ¼ *A*e/*A*a) from 1 to 10 to achieve optimal performance. With increasing area ratio, we supply enough heat for the absorber–

opt

spectral properties and temperature of the emitter. A spectrally

emitter to reach *T*e

by increasing the level of irradiance and

selective emitter should have high emittance for energies above

leveraging the high absorptance of the nanotube array. Thermal

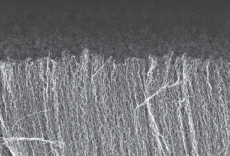
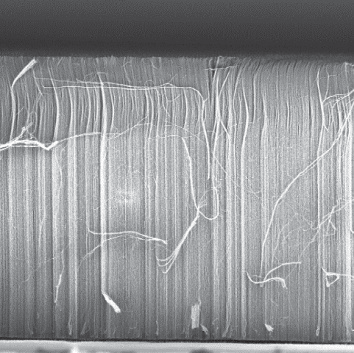
1 Device Research Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA, 2 Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA, 3 Institute for Soldier Nanotechnology, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA, 4 Department of Mechanical Engineering, Kyung Hee University, Yongin 446-701, Korea. \*e-mail: [enwang@mit.edu](mailto:enwang@mit.edu)

126 NATURE NANOTECHNOLOGY | VOL 9 | FEBRUARY 2014 | [www.nature.com/naturenanotechnology](http://www.nature.com/naturenanotechnology)

NATURE NANOTECHNOLOGY [DOI: 10.1038/NNANO.2013.286](http://www.nature.com/doifinder/10.1038/nnano.2013.286)

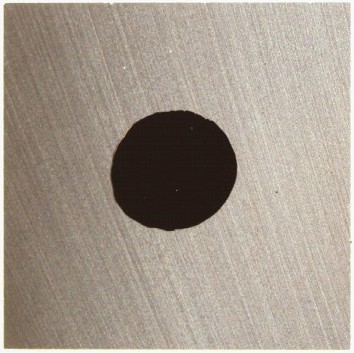
LETTERS

**c d**



2 μm

50 μm



W

MWNTs

Absorber area, *A*a

1 mm

**a** Aperture

Shield

Vacuum

Sunlight

Absorber

Thermal management

Si

Heat flow

Supports

Emitter

Thermal emission

Load

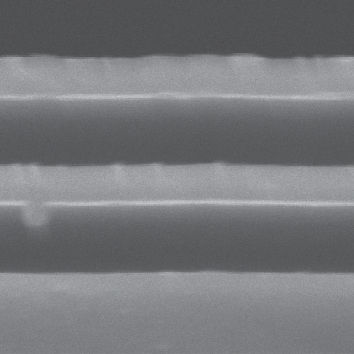
+

PV cell

−

e-h pairs

**e f**



Si

SiO2

1 μm

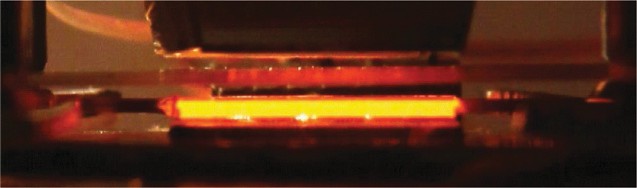


1D PhC

Emitter area, *A*e

1 mm

**b**



Aperture

Supports

Abs/Emit

PV cell

1 mm

Figure 1 | Operating principle and components of the NARO–STPV. Sunlight is converted into useful thermal emission and, ultimately, electrical power, via a hot absorber–emitter. a,b, Schematic (a) and optical image (b) of our vacuum-enclosed devices composed of an aperture/radiation-shield, an array of MWNTs as the absorber, a 1D PhC, a 0.55 eV-bandgap photovoltaic cell (InGaAsSb[19–21](#_bookmark7)) and a chilled water cooling system. c, Absorber-side optical image of

2 2

an AR (¼*A*e/*A*a) ¼ 10 module showing spatially deﬁned MWNTs (*A*a ¼ 0.1 cm ) on a tungsten-coated silicon substrate (1 × 1 cm

planar area, 550 mm

2

thick). d, SEM cross-section of the MWNTs. Inset: Magniﬁed view of the nanotube tips. e, Optical image of the 1D PhC emitter (*A*e ¼ 1 cm ). f, SEM

cross-section of the 1D PhC showing the alternating layers of silicon and SiO2.

resistance between the absorber and emitter is minimized by inte- grating the absorber and emitter on the same conductive silicon substrate such that heat is effectively delivered to the emitter via thermal spreading. Because the absorber area is reduced with respect to the planar area of the sample [(Fig.](#_bookmark0) 1c), the area for re- emissive losses from the nearly blackbody nanotube array surface is decreased, thus boosting thermal efﬁciency. To reduce parasitic radiative losses, we metallized the sides of the silicon substrate and inactive area around the nanotube absorber with tungsten, a relatively low-emissivity, high-temperature material, and incorpor- ated a high-reﬂectivity silver-coated shield [(Fig.](#_bookmark0) 1a) to recycle this parasitic radiation back to the device.

Vertically aligned carbon nanotubes were chosen as the solar absorber because of their high-temperature stability in vacuum and their nearly ideal absorptance, crucial for absorbing highly con- centrated irradiance at elevated emitter-to-absorber area ratios. As shown in [Fig. 1d,](#_bookmark0) the as-grown nanotubes are 10–15 nm in outer

diameter and 80–100 mm tall, with an ～0.5 mm variation in

height at the tips. The broad–spectrum absorptance of the nanotube array in this study exceeds 0.99 (Supplementary section ‘Absorber characterization’), consistent with previous reports for similar nano- tube array geometries[22–24](#_bookmark10).

The multilayer Si/SiO2 structure of the photonic crystal, composed of ﬁve alternating layers of silicon and SiO2 ([Fig. 1e,f](#_bookmark0)), improves the spectral matching between the emittance of the emitter and the internal quantum efﬁciency of the InGaAsSb photovoltaic cell[25–27](#_bookmark11) (*E*g ¼ 0.55 eV). These materials were chosen for ease of fabrication and high-temperature compatibility with the silicon substrate. The layer thicknesses were optimized via a constrained global optimiz- ation of the product of efﬁciency and power density[6](#_bookmark18).

Our mechanical system ensures alignment and gap control while minimizing parasitic conduction losses (Supplementary section ‘Experimental set-up’). The entire experimental layout was main- tained in vacuum (,0.5 Pa) to suppress convective and conductive heat transfer through the environment. We used a xenon-arc light

source to simulate the solar spectrum and to supply a range of irradiances *H* from 10 to 75 W cm22.

s

To gain more insight into the complex energy conversion in our

nanophotonic area-ratio optimized (NARO) STPV devices and compare it to theoretical predictions, we conducted two

0.50

*ε*e,λ

IQEpv

Experiment SQ1DD model

1.0

0.0

1

2 3

*λ* (μm)

4 5

0.45

0.40

IQE, *ε*λ

0.35

0.30

*P*out (W cm−2)

0.25

0.20

0.15

0.10

0.05

0.00

800 900 1,000 1,100 1,200 1,300

*T*ae (K)

Figure 2 | TPV characterization. Electrical output power density (*P*out) generated by the InGaAsSb photovoltaic cell as a function of the 1D Si/SiO2 PhC emitter temperature. Inset: Measured[4](#_bookmark16) spectral emittance (1*l*) of the 1D PhC at 1,285 K and the internal quantum efﬁciency (IQE) of the photovoltaic used by the SQ1DD model. The model prediction (solid line) shows excellent agreement with experimental points (symbols). Error bars represent 95% conﬁdence interval (see [Methods](#_bookmark6)).

NATURE NANOTECHNOLOGY | VOL 9 | FEBRUARY 2014 | [www.nature.com/naturenanotechnology](http://www.nature.com/naturenanotechnology) 127

LETTERS

NATURE NANOTECHNOLOGY [DOI: 10.1038/NNANO.2013.286](http://www.nature.com/doifinder/10.1038/nnano.2013.286)

**a** 0.50

0.45

0.40

0.35

0.30

*P*out (W cm−2)

0.25

0.20

0.15

0.10

0.05

*T*ae (K) 1,300

AR = 1

3

5

7

10

1,200

1,100

1,000

**b** 3.5

3.0

*H*s = 48 W cm−2

*H*s = 20 W cm−2

2.5

*η*t*η*tpv (%)

2.0

1.5

1.0

0.00

0 20 40 60 80

*H*s (W cm−2)

0.5

2 4 6 8 10

AR

**c**

3.5

1,000

*T*ae (K)

1,100 1,200 1,300

**d** 4.0

*T*ae = 1,285 K

*T*ae = 1,055 K

AR = 10

7

3

1

3.0 3.5

2.5 3.0

2.0

*η*t*η*tpv (%)

1.5

1.0

2.5

*η*t*η*tpv (%)

2.0

1.5

0.5

0.0

0 0.1 0.2 0.3 0.4 0.5

*P*out (W cm−2)

1.0

2 4 6 8 10

AR

Figure 3 | Performance characterization and optimization of the nanophotonic STPV device. a, Electrical output power density (*P*out) and absorber–emitter temperature (*T*ae determined from [Fig.](#_bookmark1) 2) with increasing *H*s (input solar power normalized by the aperture area) for AR ¼ 1 to 10. As the area ratio is increased, the device operates in a regime of decreased *sT*ae[4](#_bookmark16)/*H*s , which is favourable for the absorber efﬁciency of the nanotube array. b, Conversion

22

efﬁciency (concentrated solar to electrical, *h*t*h*tpv) with increasing area ratio for ﬁxed *H*s ¼ 20 and 48 W cm

. Competing effects of the thermal efﬁciency

and the TPV efﬁciency lead to an optimal area ratio for a ﬁxed *H*s. c, Conversion efﬁciency as a function of *P*out or, equivalently, *T*ae (AR ¼ 5 omitted for clarity). d, At a given *P*out or *T*ae, the conversion efﬁciency increases with increasing area ratio, which is attributed to an increase in thermal efﬁciency. Markers are experimental points (error bars represent 95% conﬁdence interval; see [Methods](#_bookmark6)) and solid bands represent the SQ1DD model, treating *H*s as collimated or diffuse sets the upper and lower bounds, respectively.

independent experiments: TPV and STPV. We investigated the maximum output power density (*P*out) of the photovoltaic diode as a function of the absorber–emitter temperature *T*ae in the TPV

experiment, and irradiance *H*s in the STPV experiment. The temp- erature measurement in the TPV characterization was achieved by

bonding a ﬁne-gauge thermocouple directly to the absorber side of the substrate.

As shown in [Fig.](#_bookmark1) 2, the output power of the photovoltaic cell is highly temperature-dependent, as higher energy modes (.*E*g) are excited with increasing emitter temperature. These experimental results are supported by a spectral quasi-1D diffuse radiative

network model (SQ1DD). Our model assumes isothermal operation of the absorber–emitter (that is, *T*a ¼ *T*e ¼ *T*ae) and accounts for the experimentally measured spectral properties of the components and

the geometrical conﬁguration of our planar STPV layout (Supplementary section ‘Modelling’). The results of the TPV exper- iment serve as validation of our model and provide an indirect method for determining the absorber–emitter temperature from the measured output power. This approach was used in the STPV characterization because a direct *in situ* measurement of the absor- ber–emitter temperature increases parasitic losses and reduces efﬁciency.

With the TPV performance characterized, we investigated the full energy conversion processes in our NARO–STPVs with increas- ing emitter-to-absorber area ratios. [Figure 3a](#_bookmark2) shows the electrical output power of the STPV devices as a function of irradiance *H*s

and absorber–emitter temperature (determined using the relation

between *P*out and *T*ae shown in [Fig.](#_bookmark1) 2). The upper and lower

128 NATURE NANOTECHNOLOGY | VOL 9 | FEBRUARY 2014 | [www.nature.com/naturenanotechnology](http://www.nature.com/naturenanotechnology)

NATURE NANOTECHNOLOGY [DOI: 10.1038/NNANO.2013.286](http://www.nature.com/doifinder/10.1038/nnano.2013.286)

LETTERS

estimates of our SQ1DD model (associated with treating *H*s as 20

10 × 10 cm2 NARO-STPV MWNT-1D PhC-InGaAsSb

High-quality PV cell

+ sub-bandgap filter

collimated or diffuse, respectively) bound the data within the

experimental uncertainty.

The effect of increasing area ratio is manifested in shifting the operating points to a regime of increased irradiance *H*s relative to

the thermal re-emission loss (*sT*ae[4](#_bookmark16)). If we consider the absorber 15

solar collection efﬁciency (a major component of the thermal efﬁ-

ciency) for a blackbody surface

a = 1 −

*h*BB

*sT*ae

*H*s

4

(1)

10

we observe that decreasing the *sT*ae[4](#_bookmark16)/*H*s ratio results in higher absor- ber efﬁciency (*s* is the Stefan–Boltzmann constant). For our nearly blackbody nanotube absorbers, this regime corresponds graphically to the lower right corner of [Fig. 3a.](#_bookmark2) Using equation (1), we estimated

that the absorber efﬁciency for AR ¼ 10 is above 75%.

Nevertheless, absorber efﬁciency is only a component of the overall STPV efﬁciency. Indeed, the efﬁciency of converting concen- trated sunlight into electrical power (*h*t*h*tpv) does not monotonically increase with increasing area ratio for a ﬁxed irradiance *H*s. As shown in [Fig. 3b,](#_bookmark2) an optimal area ratio exists. To understand why this optimal area ratio arises, the competing effects of the thermal efﬁciency and the TPV efﬁciency are considered. The thermal efﬁ-

ciency is signiﬁcantly enhanced as the area ratio increases due to a rise in absorber efﬁciency (as explained above). In contrast, with

increasing area ratio for ﬁxed *H*s, the operating temperature of the absorber–emitter decreases because the ratio of the absorbed solar

power (～*A*a*H*s) relative to the thermal emission (～*A*e*sT*ae[4](#_bookmark16))

decreases, ultimately leading to a decrease in TPV efﬁciency as the

opt

4

10

*η*t*η*tpv (%)

7

5

3

3

1 × 1 cm2 NARO-STPV

MWNT-1D PhC-InGaAsSb

2

>200

Wcm−2

1

AR = 1

(ref. 9)

*ε*λ = 0.5, AR = 1

0

20 40 60 80 100

*H*s (W cm−2)

Figure 4 | Relative improvements in efﬁciency and near-term predictions

temperature drops signiﬁcantly below *T*e

. These two competing

for NARO–STPVs. Conversion efﬁciency *h h*

as a function of a solar

effects lead to an optimal area ratio for a ﬁxed irradiance or, equiva- lently, for a ﬁxed optical concentration (10 times ¼ 1 W cm22, ASTM E772). In general, the optimum area ratio increases with optical concentration, as shown in [Fig. 3b,](#_bookmark2) where the optimum

shifts from approximately AR ¼ 2 to AR ¼ 5 as *H*s increases from 20 to 48 W cm22.

Using the relation between *P*out and *T*ae [(Fig.](#_bookmark1) 2), we investigated the system performance as a function of absorber–emitter tempera- ture. [Figure 3c](#_bookmark2) shows that the efﬁciency initially increases sharply

with emitter temperature (below 1,200 K) as modes with energies above *E*g are increasingly excited. As the temperature approaches *T*opt, the efﬁciency plateaus as increasing useful emission (that is,

e

radiation at *E* . *E*g) is balanced by increasing re-emission losses and photovoltaic inefﬁciencies associated with high photocurrents. Increasing the area ratio for a given absorber–emitter temperature

results in increased conversion efﬁciency [(Fig.](#_bookmark2) 3d). Because the TPV efﬁciency is determined by the emitter temperature, the rela- tive increase in conversion efﬁciency (*h*t*h*tpv) is completely attribu-

opt

t tpv

irradiance *H*s. Contributions to *h*t*h*tpv relative to a greybody absorber– emitter: MWNT–1D PhC absorber–emitter (twofold improvement) and area

ratio optimization (additional twofold improvement). Efﬁciencies approaching 20% were predicted with a scaled-up (10 × 10 cm2) NARO–STPV utilizing a

high-quality 0.55 eV photovoltaic module with a sub-bandgap reﬂector[20](#_bookmark8). All points and predictions were made using the SQ1DD model (*H*s was treated as collimated).

this work, can be easily implemented in future STPV designs to increase overall efﬁciency.

From the SQ1DD model, our highest-efﬁciency operating point corresponds to a temperature of 1,235 K with 54% thermal efﬁ- ciency and 5.8% TPV efﬁciency. As the device scales in planar

area from 1 × 1 cm2 to 10 × 10 cm2 [(Fig.](#_bookmark3) 4), the thermal efﬁciency should improve to ～75% as parasitic losses to the inactive area and

mechanical supports decrease from 91% to 20% of the useful emis- sion (Supplementary Fig. 5). Another important aspect limiting our

ted to the increase in thermal efﬁciency. At *T*e

(1,285 K), we

conversion efﬁciency is the performance of the photovoltaic cell

experimentally demonstrated a twofold increase in thermal efﬁ-

ciency from AR ¼ 1 to AR ¼ 5.

Overall, the highest conversion efﬁciency (*h*t*h*tpv) that we measured was 3.2+0.2% using an AR ¼ 7 device, which is three times greater than that obtained in previous STPV experiments[9](#_bookmark19).

This was achieved using a compact design at substantially lower levels of optical concentration (～750 times), which enables higher

optical efﬁciencies. As shown in [Fig.](#_bookmark3) 4, signiﬁcant enhancements in efﬁciency relative to a greybody absorber–emitter (1 ¼ 0.5) were achieved through the use of (1) a 1D PhC for improved spectral performance of the emitter and a vertically aligned MWNT array for nearly ideal solar absorptance (a twofold contribution to the

improvement in *h*t*h*tpv) and (2) optimization of the active emitter-to-absorber area ratio (an additional twofold improvement). Optimizing the area ratio at a ﬁxed optical concentration with a

nanophotonic absorber–emitter, experimentally demonstrated in

(*V*oc ¼ 0.57*E*g, 0.48 ﬁll factor, 83% active area). Using an improved, yet realistic 0.55 eV InGaAsSb cell (*V*oc ¼ 0.70*E*g, 0.74 ﬁll factor, 90% active area) and a sub-bandgap photon reﬂecting ﬁlter[26](#_bookmark12), the

STPV efﬁciency should approach 20% at moderate optical concen- trations [(Fig.](#_bookmark3) 4). Although this result requires a scale-up of our pro- cessing and experimental systems, the present experimental demonstration of a STPV with 1 cm2 nanophotonic absorber– emitter validates our model. Moreover, the efﬁciency can be further enhanced through improvements in low-bandgap photovol- taics (such as GaSb, germanium and graphene-based photovoltaics),

better spectral control[5,15,21](#_bookmark17) and higher-temperature operation. Unlike silicon photovoltaic cells that have reached ～85% of their

thermodynamic efﬁciency, the best-performing low-bandgap (TPV) cells exhibit 30–50% of their thermodynamic efﬁ- ciency[10,25,26,28](#_bookmark20). By re-optimizing the geometry of the 1D PhC, our nanophotonic absorber–emitter may be paired with photovoltaic

NATURE NANOTECHNOLOGY | VOL 9 | FEBRUARY 2014 | [www.nature.com/naturenanotechnology](http://www.nature.com/naturenanotechnology) 129

LETTERS

NATURE NANOTECHNOLOGY [DOI: 10.1038/NNANO.2013.286](http://www.nature.com/doifinder/10.1038/nnano.2013.286)

bandgaps up to ～0.7 eV. Beyond this point, higher-temperature

photonic-crystal materials, such as refractory metals[18](#_bookmark9), are required. The efﬁciency improvements demonstrated in this work, as well as the promising predictions using a validated model, suggest the viability of nanophotonic STPVs for efﬁcient and scalable solar energy conversion.

# Methods

The absorber and emitter were prepared using conventional physical and chemical vapour deposition (PVD, CVD) processes. The polycrystalline silicon and SiO2 layers of the 1D photonic-crystal emitter were deposited by low-pressure and plasma-enhanced chemical vapour deposition, respectively[6](#_bookmark18). The wafer was

annealed after each deposition. On the back side of the emitter, a 10 nm adhesion layer of titanium was sputtered on the substrate, followed by a 200 nm layer of tungsten. Using a laser-cut acrylic contact mask, a seed layer for CNT growth was deposited onto the samples with electron-beam evaporation. The CNTs were grown using a high-temperature CVD process in a H2/He environment by modifying a

previously developed procedure[29](#_bookmark13). The samples were heated to 720 8C from

room temperature in ～10 min and held at 720 8C for 5 min to anneal the iron seed.

CNTs were grown for 10 min at 720 8C using an ethylene gas carbon source. All ﬂowing gases were preheated to 625 8C. Following growth, the furnace was rapidly cooled in a H2/He environment.

The absorber–emitter substrate was mechanically secured using a custom spring-

loaded needle-support layout. Vacuum gaps of 400 mm and 300 mm separated

the shield from the absorber, and the emitter from the photovoltaic cell, respectively, so that the aperture/absorber and emitter/cell view factors exceeded 0.85. Manual linear stages were used to align and control the spacing between the reﬂecting shield, the absorber–emitter, and the photovoltaic cell. Experiments were conducted on each absorber–emitter pair at varying levels of ﬂux of simulated solar radiation *H*s

through the aperture (10–75 W cm22) by changing the distance between the light

source and the experiment (Supplementary section ‘Experimental set-up’). *H*s is deﬁned as the input solar power through the aperture normalized by the aperture area or, equivalently, the nanotube absorber area. *I*–*V* and temperature measurements were obtained at steady operating conditions of the STPV device. Uncertainty in the reported experimental quantities was evaluated based on

propagation of the following errors: variance (using a *t*-distribution with a 95% conﬁdence interval), instrument error and resolution error. The photovoltaic temperature was maintained near 293 K using a chilled water loop (Supplementary equation (S1)).

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# Author contributions

All authors contributed extensively to this work. A.L., D.M.B. and Y.N. envisioned and implemented the experimental studies. A.L. and D.M.B. fabricated the absorber, executed the experiments and wrote the paper. W.R.C. designed and fabricated the emitter. I.C., M.S. and E.N.W. supervised and guided the project.

# Additional information

Supplementary information is available in the [online version](http://www.nature.com/doifinder/10.1038/nnano.2013.286) of the paper. Reprints and permissions information is available online at [www.nature.com/reprints](http://www.nature.com/reprints). Correspondence and requests for materials should be addressed to E.N.W.

# Competing ﬁnancial interests

The authors declare no competing ﬁnancial interests.

130 NATURE NANOTECHNOLOGY | VOL 9 | FEBRUARY 2014 | [www.nature.com/naturenanotechnology](http://www.nature.com/naturenanotechnology)

ADDENDUM

A nanophotonic solar thermophotovoltaic device

# Andrej Lenert, David M. Bierman, Youngsuk Nam, Walker R. Chan, Ivan Celanović, Marin Soljačić and Evelyn N. Wang

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In this Letter, the equation describing *T*opt (see below; and also equation 1.133 in ref. 1) represents the temperature required for the maximum of Planck’s distribution expressed in units of wavelength to match the bandgap energy. However, the energy at which the maximum occurs depends on whether we consider energy flux per unit frequency range or per unit wavelength range2,3. A more appro- priate approximation matches the maximum of Planck’s distribution expressed in units of frequency or energy to the bandgap energy, the scaling factor in this case is 4114 K eV–1.

e

*T*opt −1

e ≈ 2336 [K eV

] · *E*g

From the experimental results presented in this Letter, however, it is evident that the peak solar thermophotovoltaic (STPV) efficiency for a 0.55 eV cell is reached at temperatures substantially lower than what the corrected scaling factor suggests. Thus, a match between the bandgap energy and the energy corresponding to the maximum emission does not fully determine the optimal temperature of the emitter, particularly not in the case of STPVs; factors not considered by this simple approximation, such as the thermalization losses in the cell, play a significant role. For a more complete discussion of optimal temperatures in practical STPV converters please refer to ref. 4.

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