Dimensionality, Feedback and Heat Trap for Nanostructure-based Thermionics

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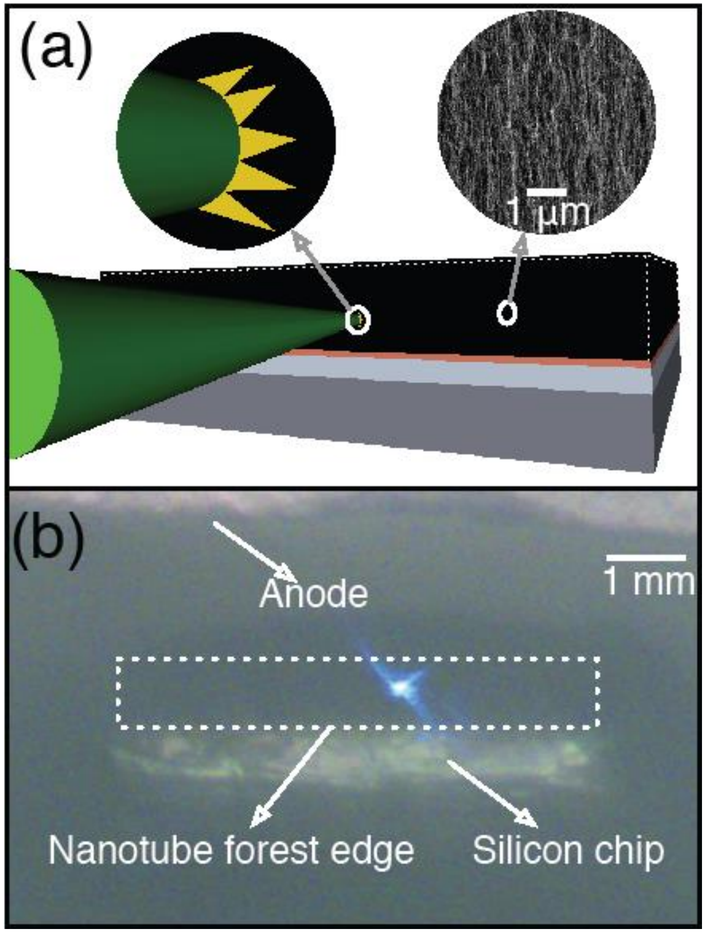
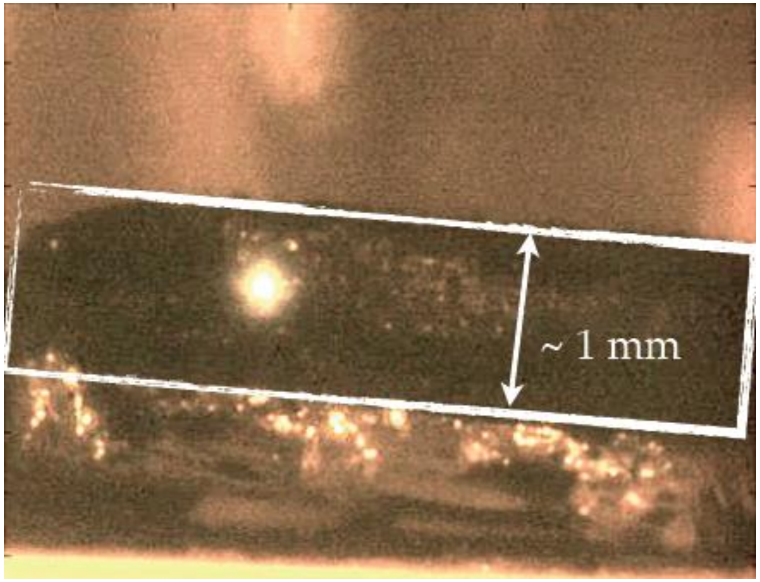
Heat Trap

Localized light-induced heating of a spot can be achieved on the side or top surface of a macroscopic-size carbon nanotube forest. The incandescence can be seen on the image below (the laser light has been filtered out using a filter in front of the camera taking the photo).

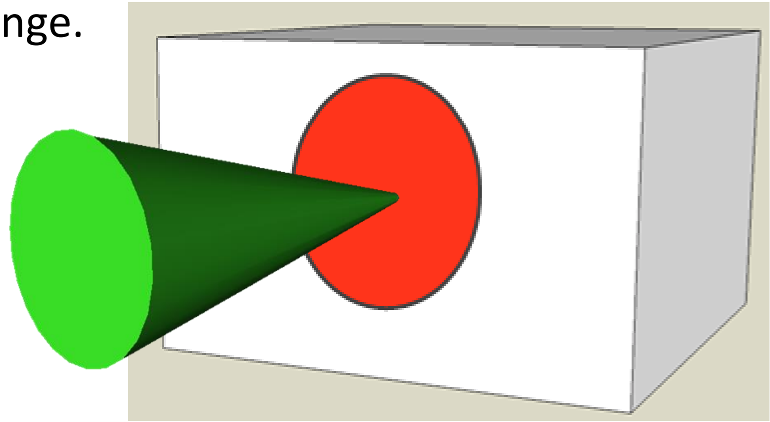


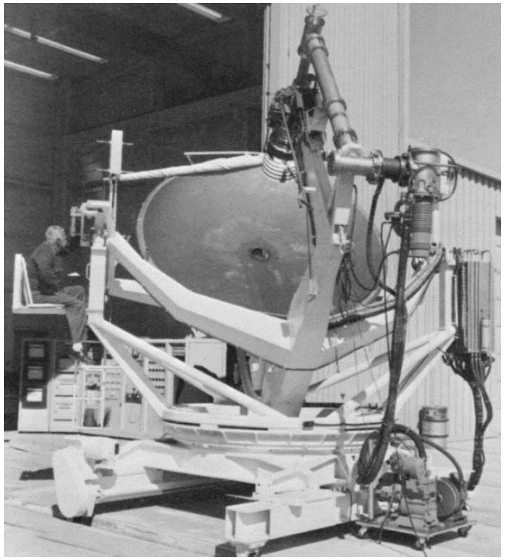


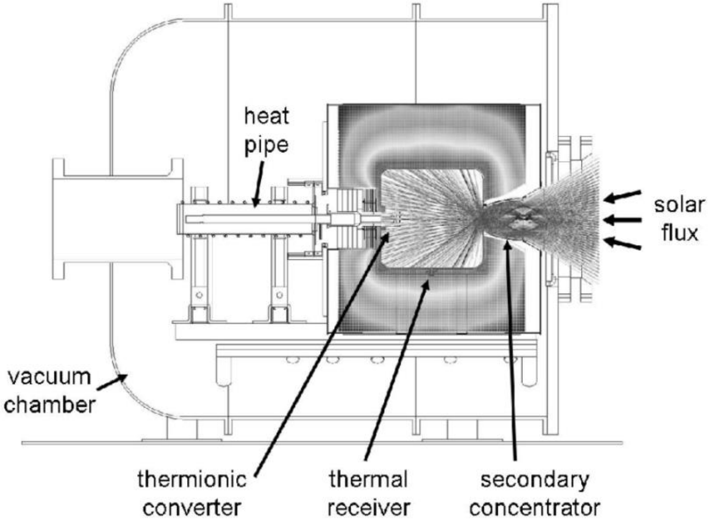
Yaghoobi, Vahdani Moghaddam, and Nojeh, Solid State Communications 151, 1105 (2011)

Light-induced thermionics

Due to thermal dissipation in the cathode because of high thermal conductivity, high optical powers are required for heating to thermionic emission temperatures. In addition, prevention of heat spread to the rest of the device is a challenge.



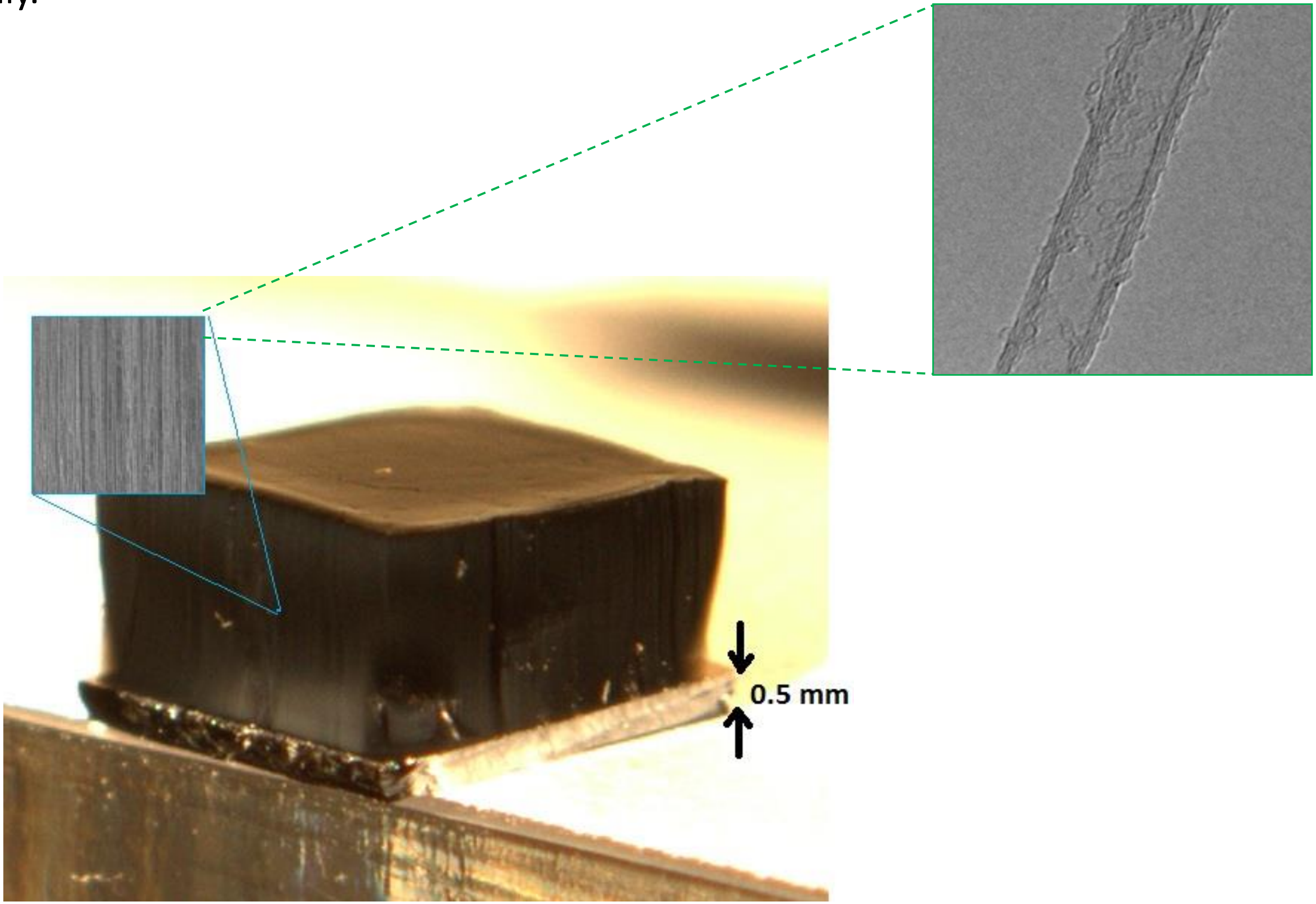




Adams, AIP Conf. Proc. 813, 590 (2006)

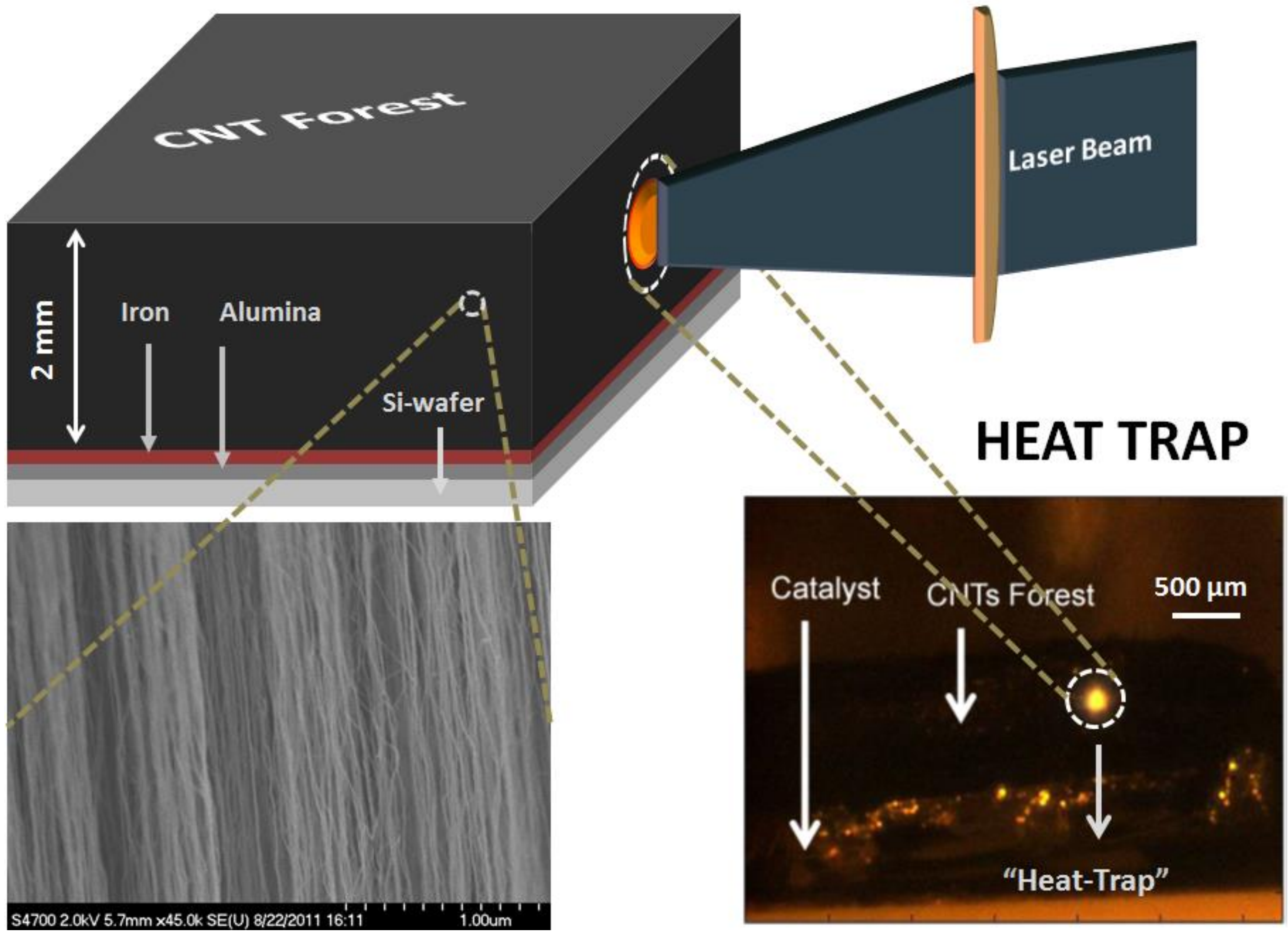
Carbon nanotube forests

Macroscopic-size forests of carbon nanotubes can be grown using chemical vapour deposition. The nanotubes can have lengths of several millimeters and are overall aligned, standing up vertically.



Heat Trap

A spot on the side (or top) surface of the forest can be illuminated by a focused beam of light. The heat generated at the illuminated spot can remain localized (trapped). This is counter intuitive as nanotubes are understood to be good thermal conductors.

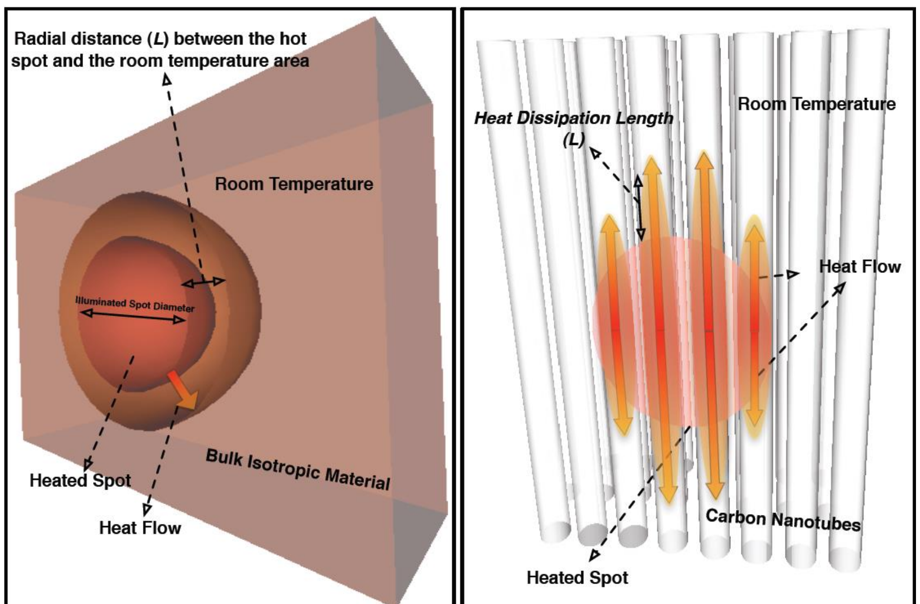


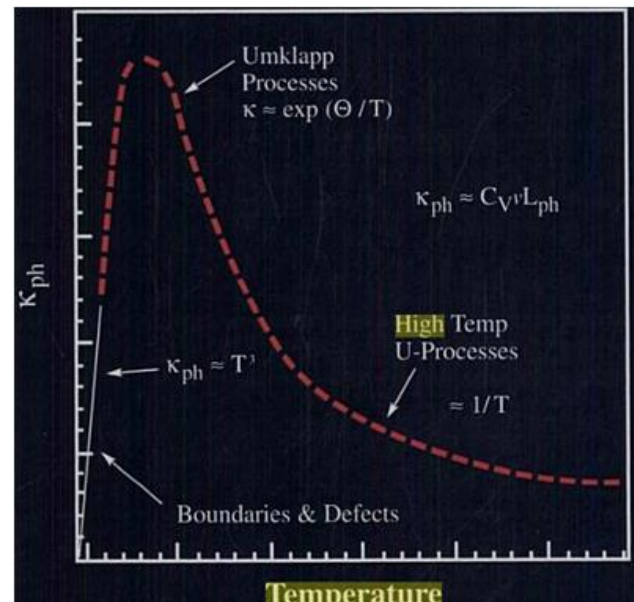
Yaghoobi, Vahdani Moghaddam, and Nojeh, Solid State Communications 151, 1105 (2011)

Heat Trap mechanism

The Heat Trap effect may be explained by the fact that heat transfer in the nanotube forest is quasi one-dimensional, plus the rapid drop of thermal conductivity with the increase of temperature. As a result, once the intensity of the illuminating optical beam is beyond a certain threshold, a positive feedback loop or avalanche process is initiated, whereby thermal conductivity is driven down at the illuminated spot and temperature is increased dramatically. The effect can be modelled by considering the power equilibrium equation in steady state.

Laser power = power lost due to electron emission +
power lost due to photon emission (black-body radiation) +
power lost due to heat transfer

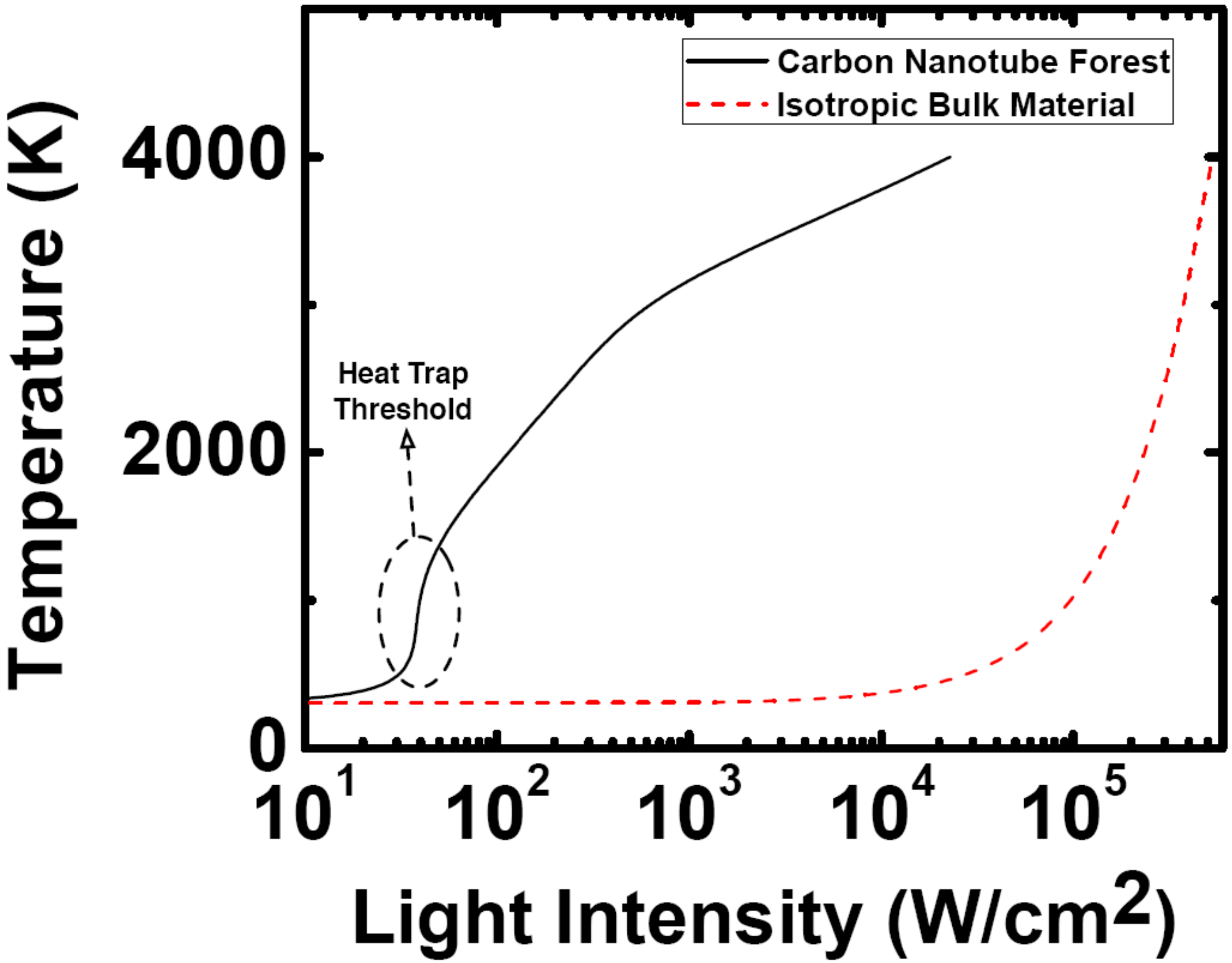




Yaghoobi, Vahdani Moghaddam, and Nojeh, AIP Advances 2, 042139 (2012)

Efficient heating

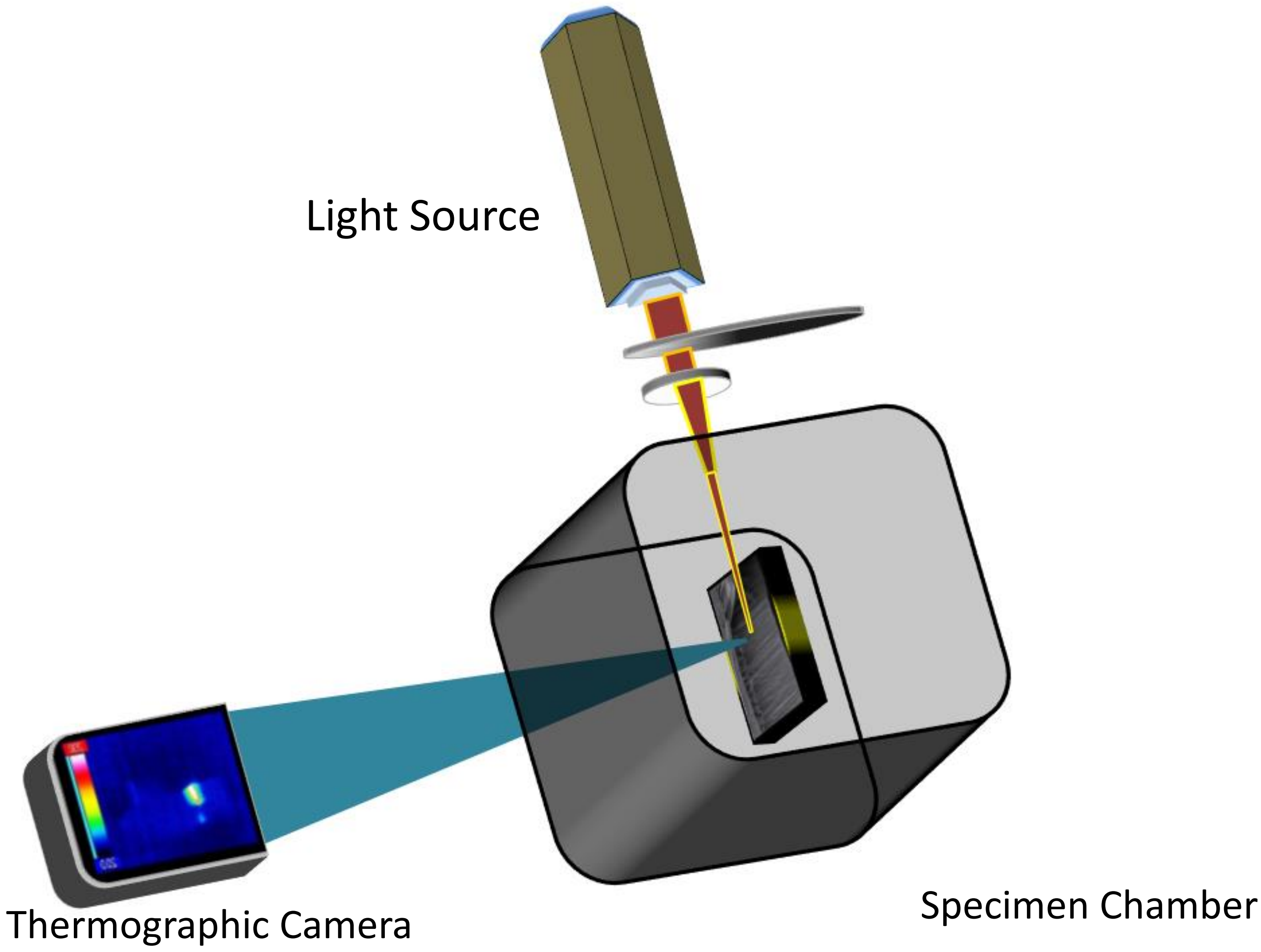
As a result of Heat Trap, nanotube forests can be heated (locally) to thermionic emission temperatures using optical intensities that are several orders of magnitude lower than those needed for substantial heating of bulk cathodes.



Yaghoobi, Vahdani Moghaddam, and Nojeh, AIP Advances 2, 042139 (2012)

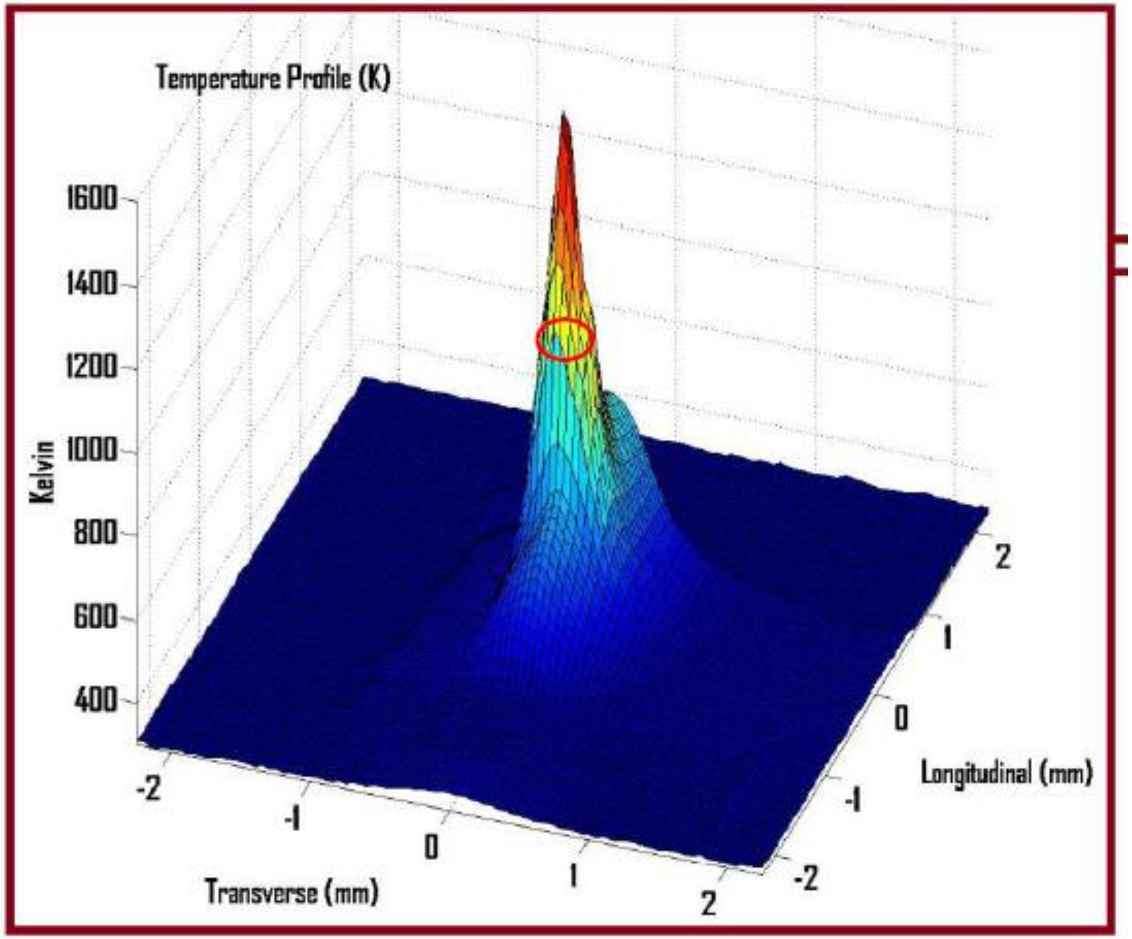
Temperature measurements

The spot's average temperature can be measured by fitting its incandescence spectrum to the black-body radiation formula. The spatial distribution of temperature can also be obtained by using a thermographic camera.



Temperature profile

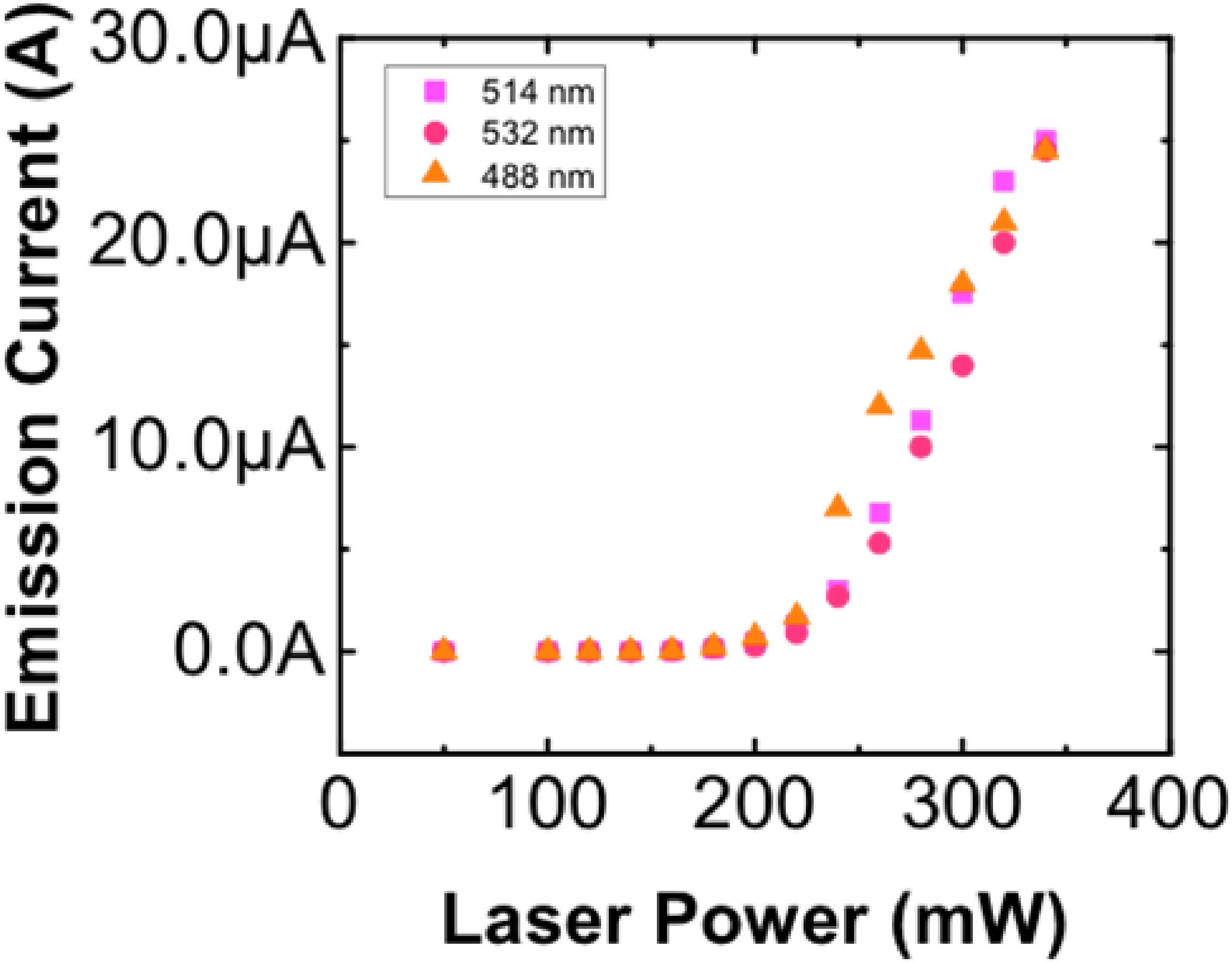
Temperature gradients higher than 1,200 K/mm are observed between the center of the illuminated spot and the surrounding areas on the nanotube forest, although this is a conductor.



Chang, Vahdani Moghaddam, Khoshaman, Mohamed Ali, Dahmardeh, Takahata, and Nojeh, 57th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN 2013), Nashville TN, USA (28-31 May 2013)

Thermionic emission

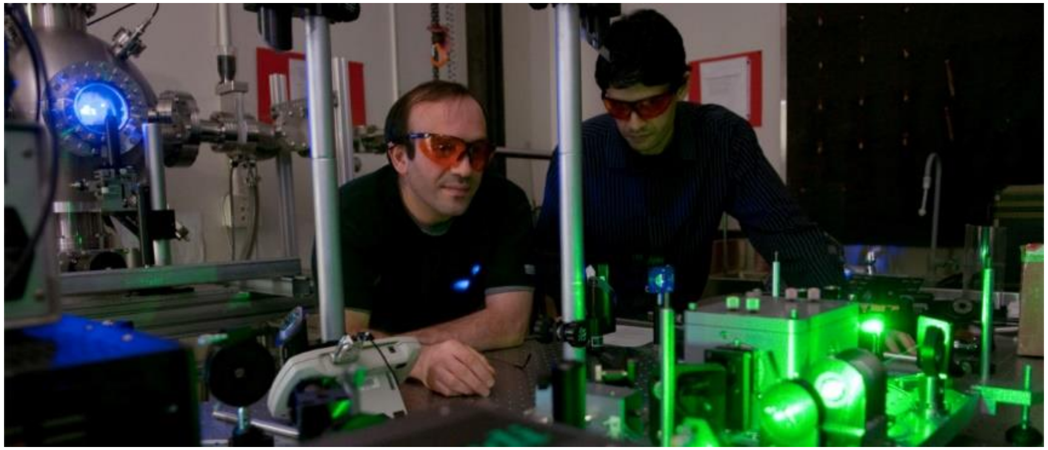
The emission current follows Richardson's law. The behaviour with optical power also depends on the spot size, of course.



Yaghoobi, Vahdani Moghaddam, and Nojeh, Solid State Communications 151, 1105 (2011)

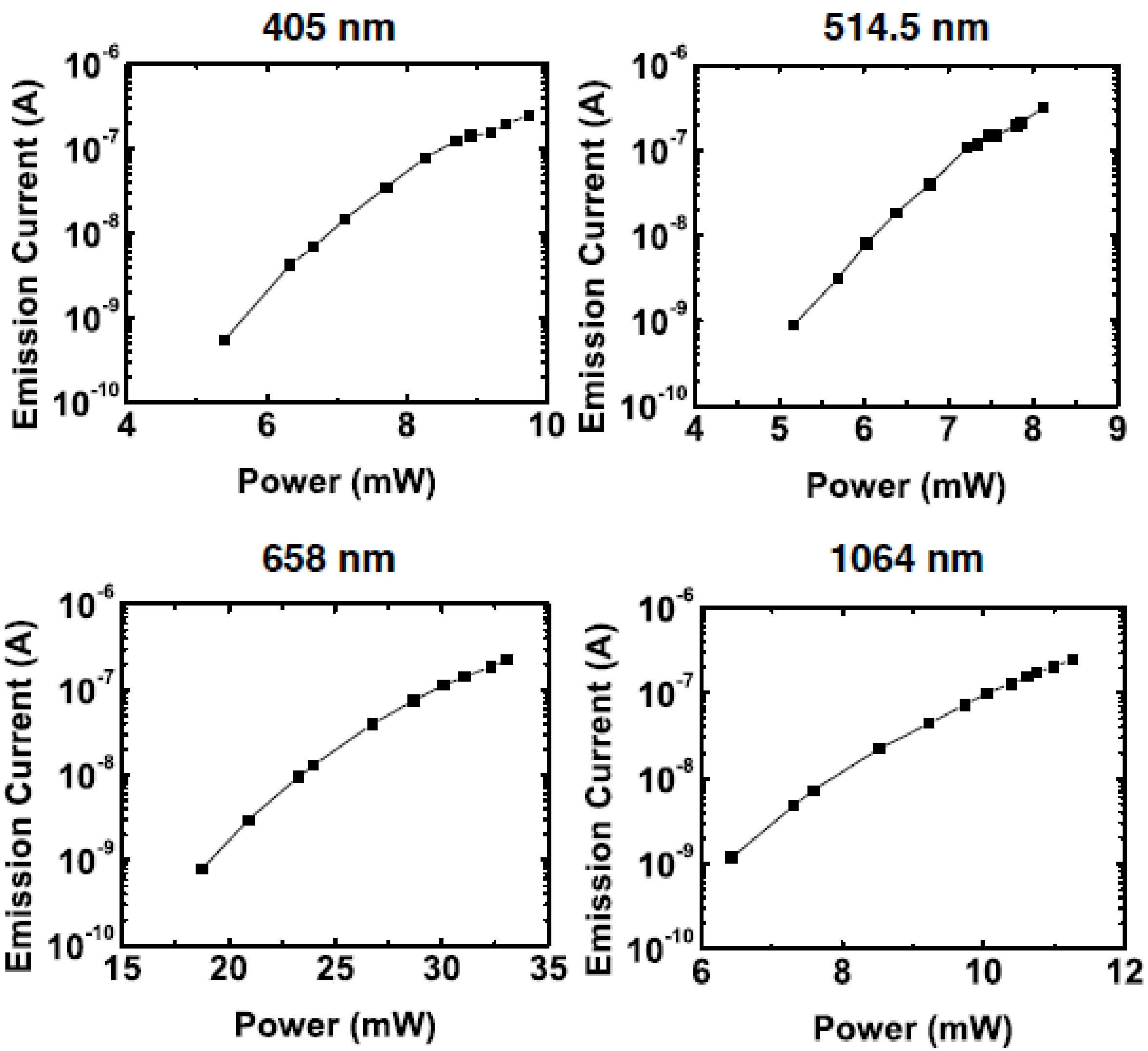
Practical consequences

Steady thermionic emission can be obtained using optical powers as low as a few milliwatts, out of a continuous light source. So, simple and inexpensive devices can be made, and we went from big UHV chambers and powerful lasers to very simple structures.



Wavelength dependence

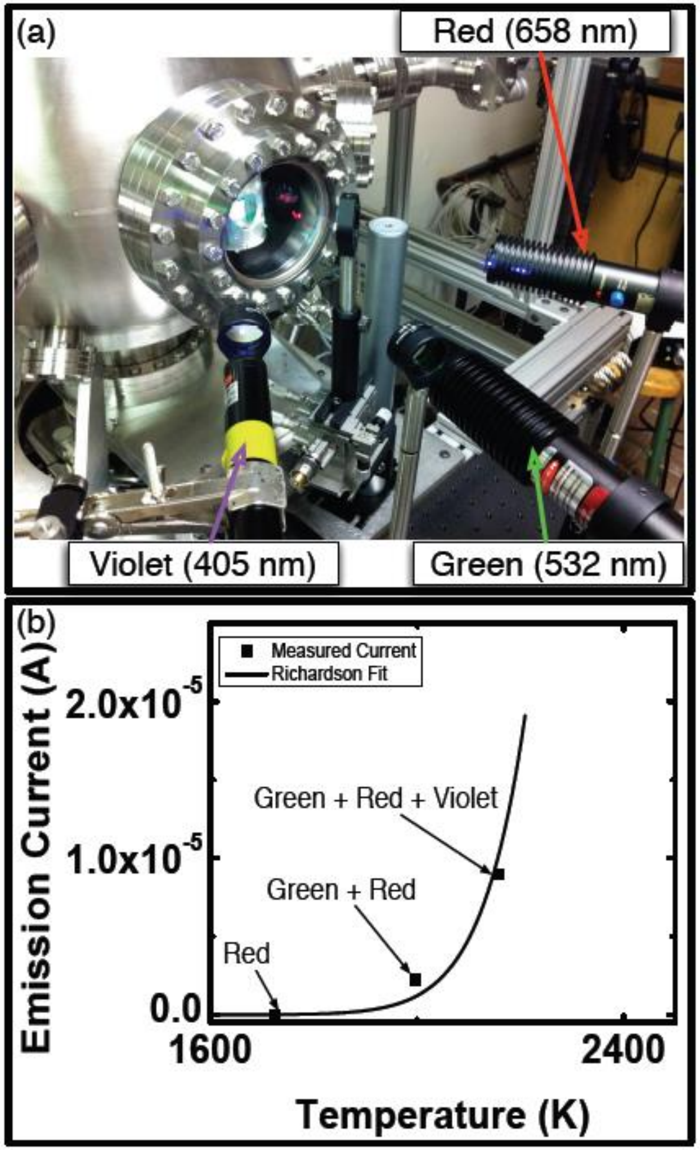
The response is quite insensitive to the wavelength of the illuminating beam (note: the graphs below haven't been normalized to the beam spot size).



Vahdani Moghaddam, Yaghoobi, and Nojeh, Applied Physics Letters 101, 253110 (2012)

Combining wavelengths

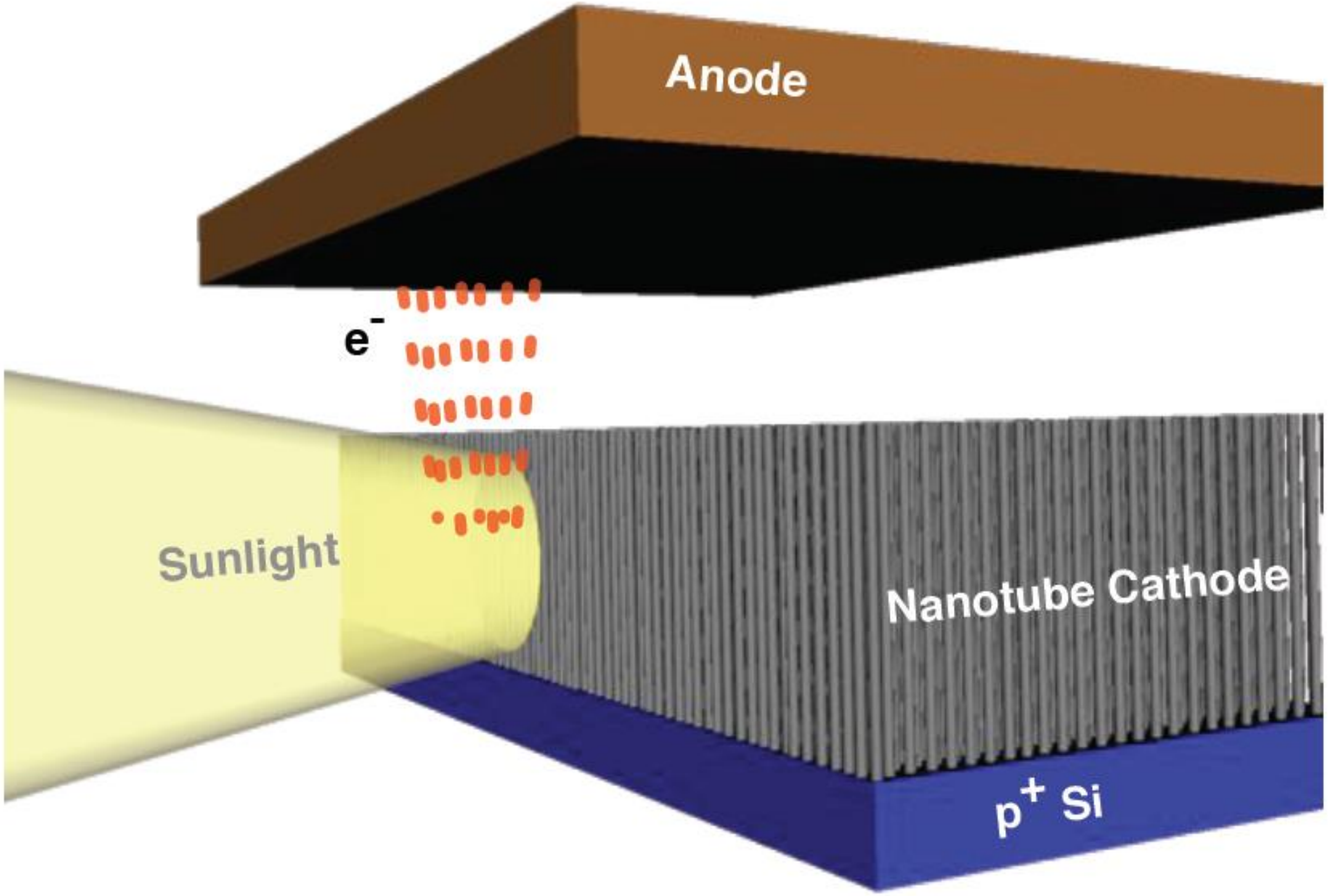
Combining different wavelengths essentially works as adding up their power.



Vahdani Moghaddam, Yaghoobi, and Nojeh, Applied Physics Letters 101, 253110 (2012)

Using an abundant source of light

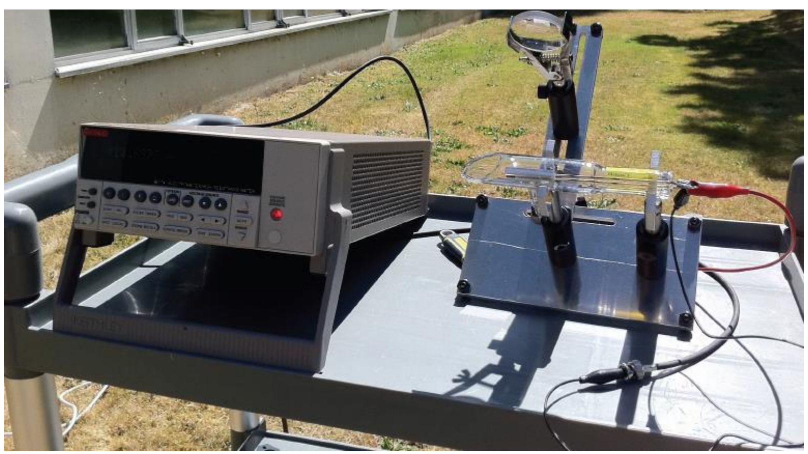
So, can this be done using sunlight?

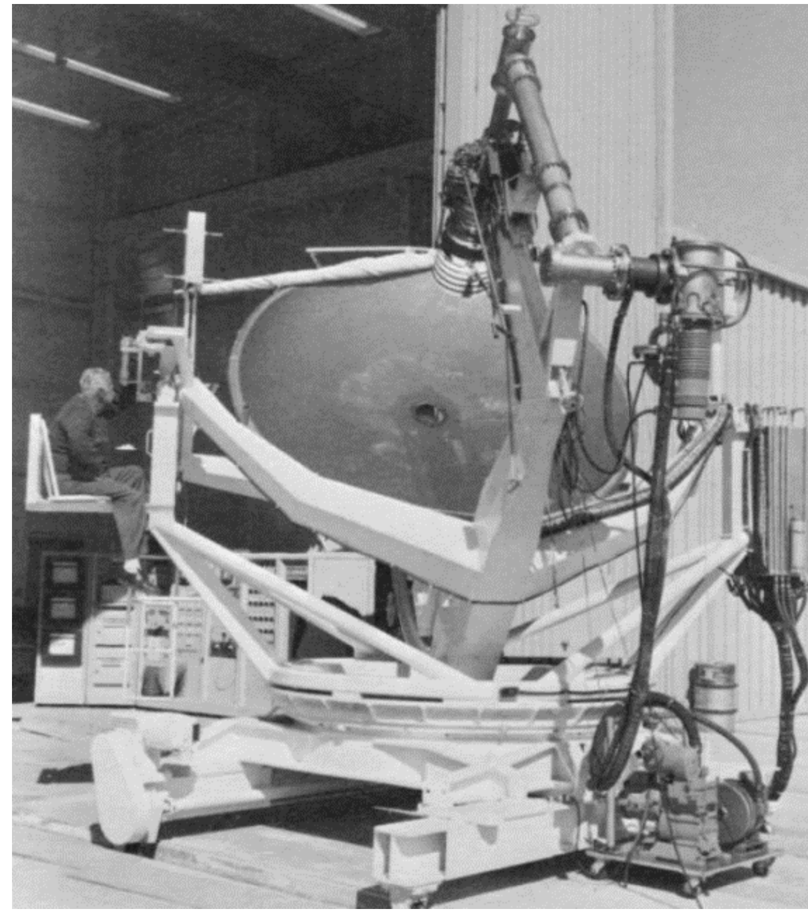


Yaghoobi, Vahdani Moghaddam, and Nojeh, AIP Advances 2, 042139 (2012)

Solar thermionics

The answer is yes, and it can be done with very modest amounts of sunlight. Compare the simple devices below (on the left) and the small size of the lens used, to the large sunlight collectors needed for heating bulk cathodes (on the right).



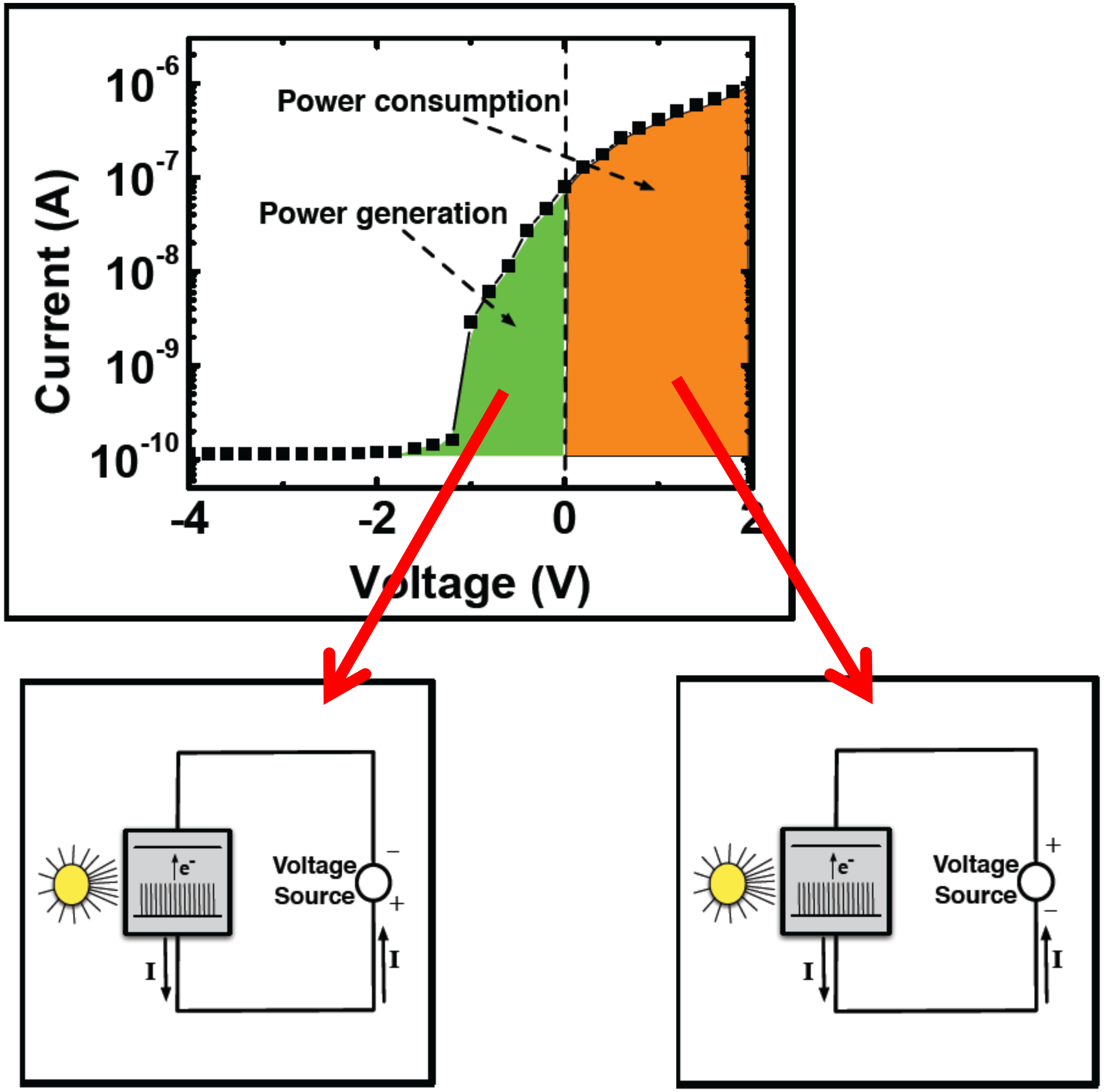


Yaghoobi, Vahdani Moghaddam, and Nojeh, AIP Advances 2, 042139 (2012)

Adams, AIP Conf. Proc. 813, 590 (2006)

On-sun testing

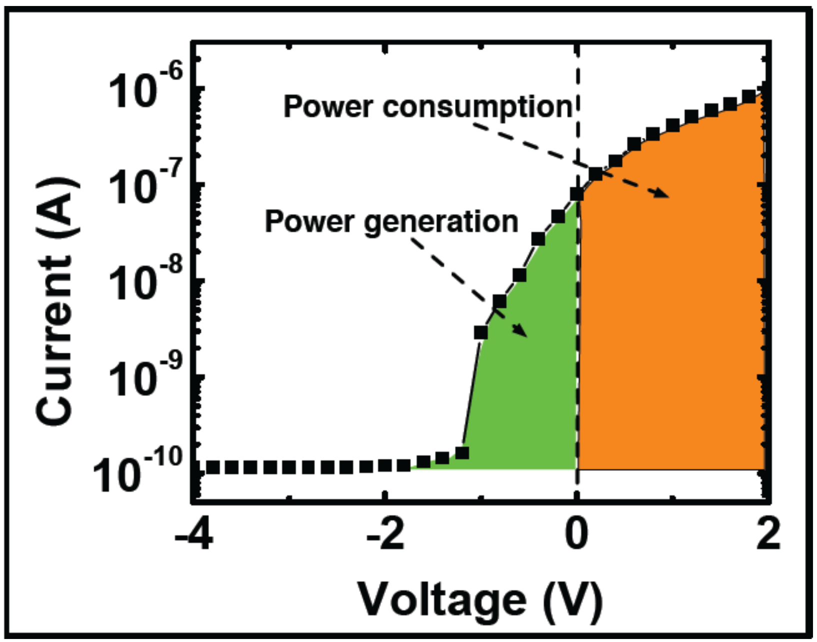
Device characteristics below show the power consumption and generation regimes. Power can also be harvested without applying any bias and by simply connecting a resistor across the two terminals of the device.

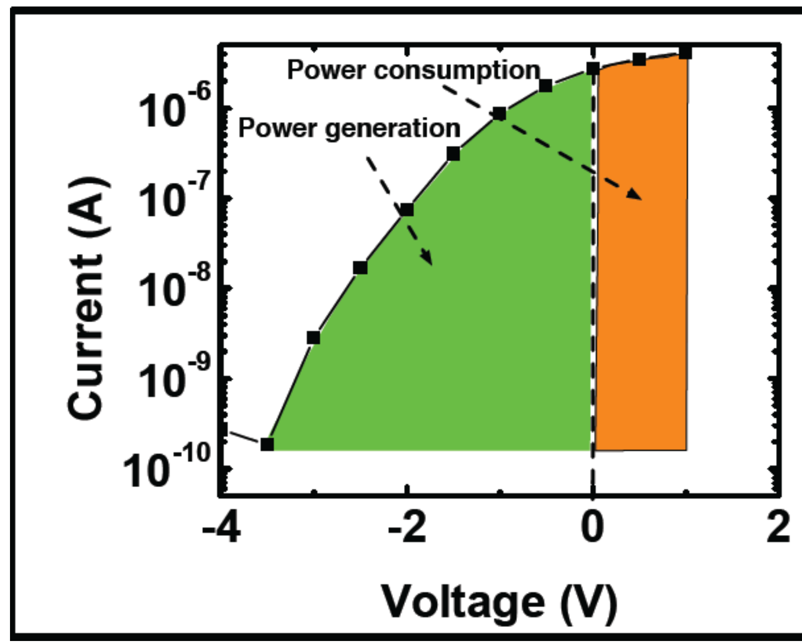


Yaghoobi, Vahdani Moghaddam, and Nojeh, AIP Advances 2, 042139 (2012)

On-sun testing

Device characteristics and efficiency can be improved significantly by using a slightly better lens (for improved focusing of sunlight) and wider anode (to improve electron collection), although overall efficiency is still very poor for our prototypes.



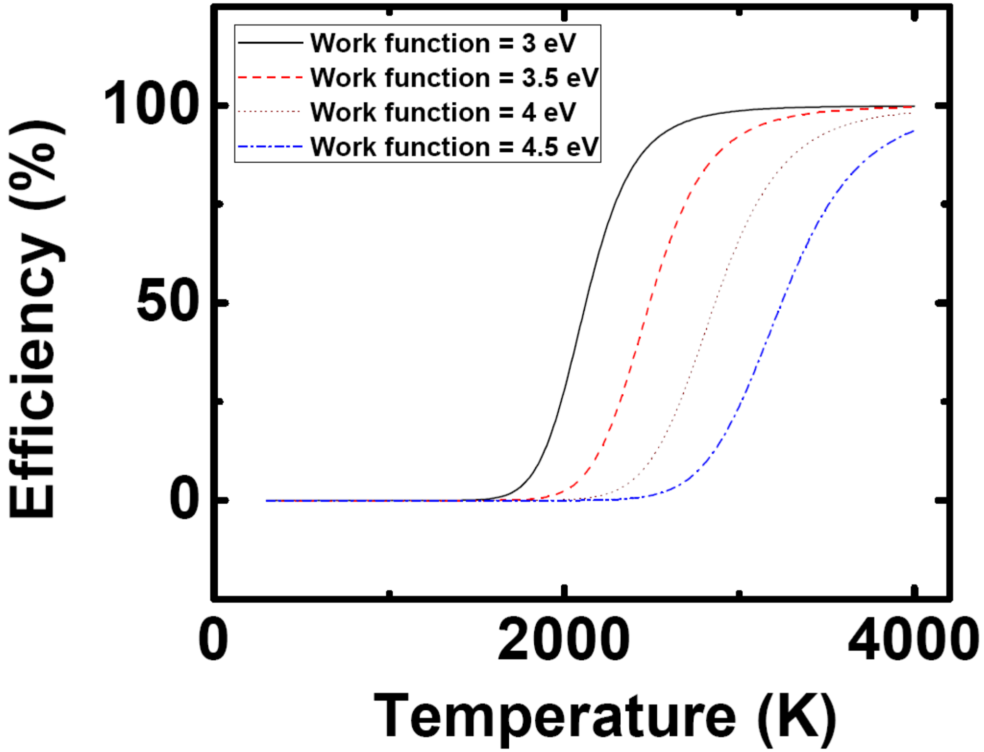


Yaghoobi, Vahdani Moghaddam, and Nojeh, AIP Advances 2, 042139 (2012)

Improving efficiency

The big source of loss at this point is incandescence. We need to reduce the workfunction, so that we can operate at lower temperatures and still get high emission current (but much lower incandescence). (Note: the curves below don't include space charge, anode workfunction, etc, and are just meant to illustrate the effect of cathode workfunction.)

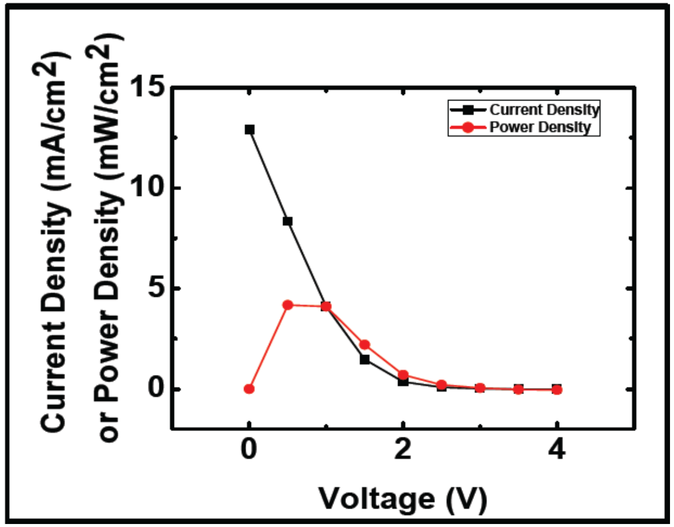
Laser power = power lost due to electron emission +
power lost due to photon emission (black-body radiation) +
power lost due to heat transfer

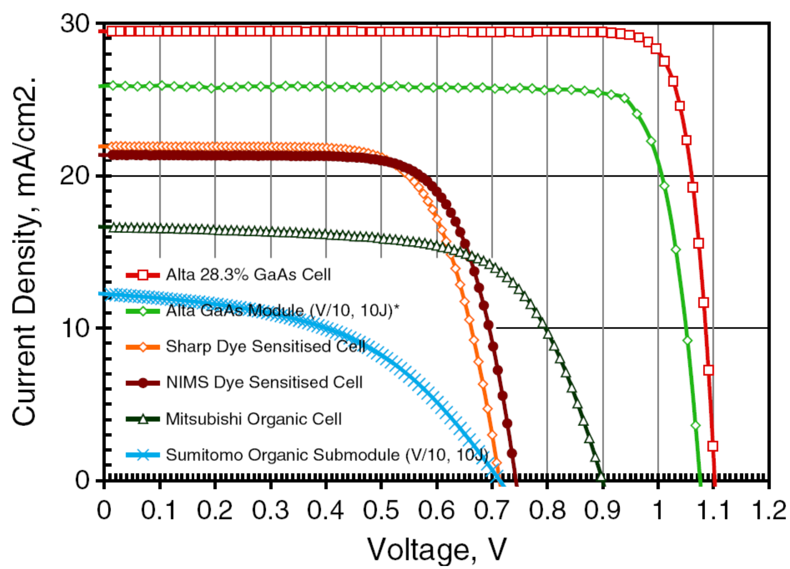


Yaghoobi, Vahdani Moghaddam, and Nojeh, AIP Advances 2, 042139 (2012)

Power and current density

Power and current density are already comparable to those of advanced photovoltaics. Output voltage is also quite good.



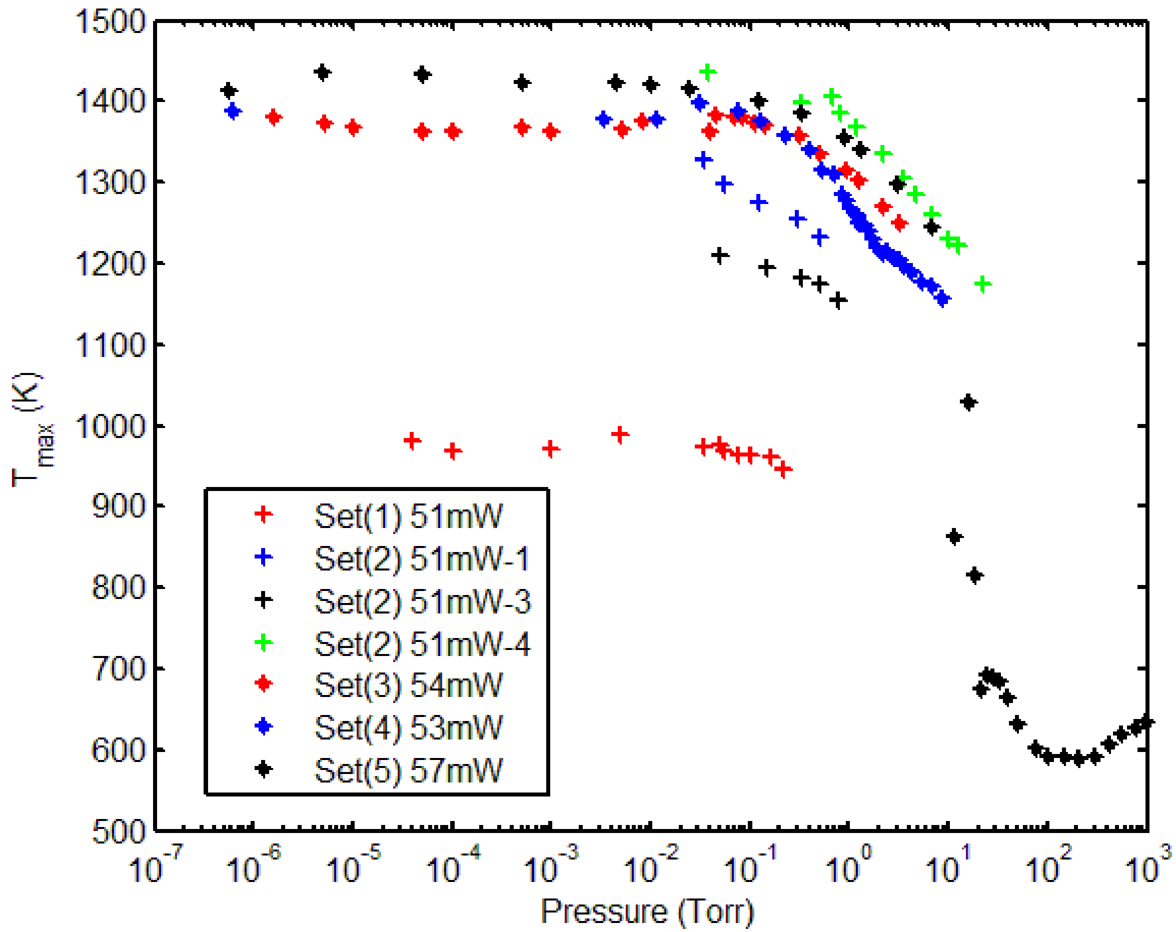


Prog. in PV.: Res. & App. 20, 12 (2012)

Yaghoobi, Vahdani Moghaddam, and Nojeh, AIP Advances 2, 042139 (2012)

Effect of vacuum level

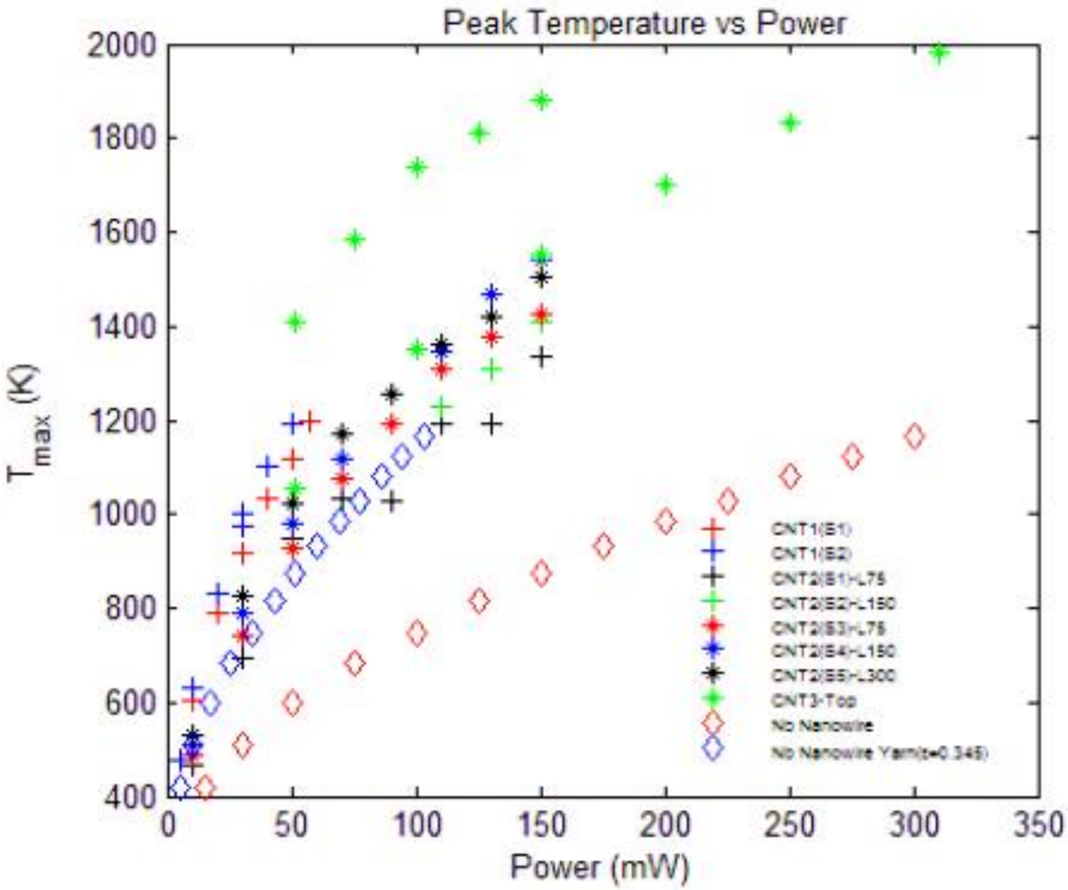
The effect works even in poor vacuum.



Chang, Dahmardeh, Vahdani Moghaddam, Mirvakili, Madden, Takahata, and Nojeh, 58th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN 2014), Washington DC, USA (27-30 May 2014)

Heat Trap unique to nanotubes?

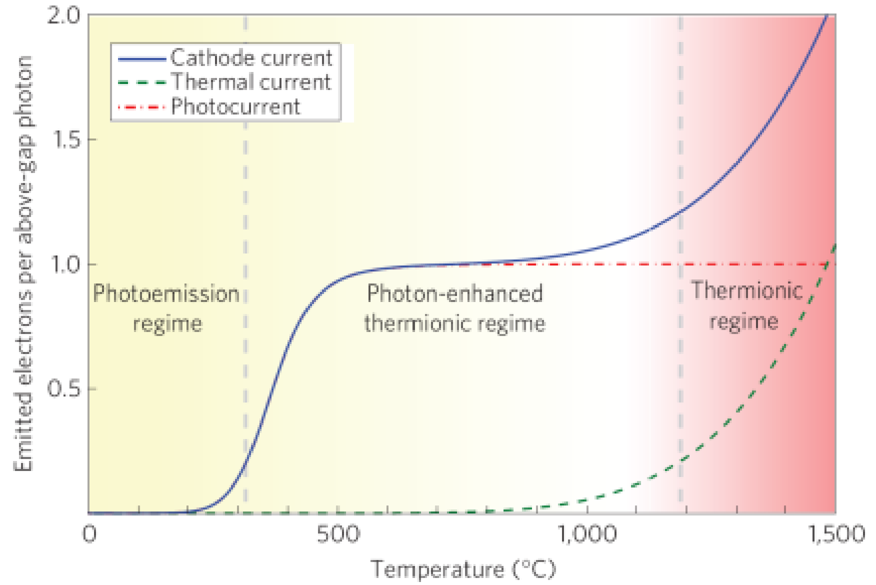
Not necessarily. This might be a property of one-dimensional systems in general. We have also observed it with niobium nanowires, although they don't seem to withstand the high temperatures as nicely as nanotubes.



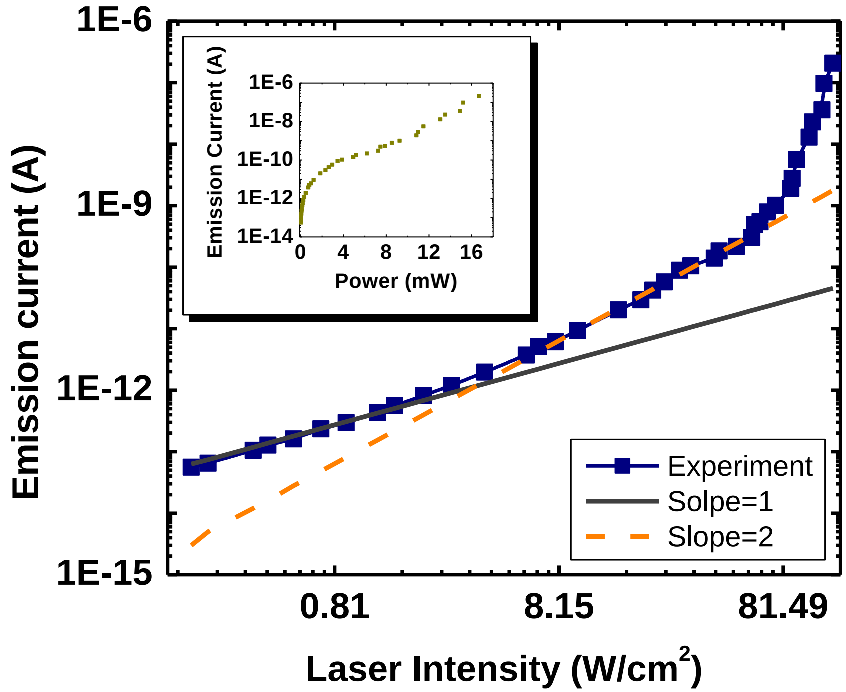
Chang, Dahmardeh, Vahdani Moghaddam, Mirvakili, Madden, Takahata, and Nojeh, 58th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN 2014), Washington DC, USA (27-30 May 2014)

Multi-photon photo/thermionic emission

If we use a light source with sufficient photon energy for photoemission, such as a 266-nm laser (photon energy of 4.66 eV, just around or over the workfunction of nanotubes), we see both photoemission and thermionic emission, and their combined effect. The behaviour resembles the PETE effect. The slope of 2 on the log-log plot of emission current vs. intensity suggests 2-photon photoemission. The behaviour matches the generalized Fowler-DuBridge theory well, although the coefficient of 2-photon photoemission comes out to be several orders of magnitude higher than that of metals like tungsten and molybdenum. (2-photon photoemission is seen at very low optical intensities relatively to those used for those metals.)



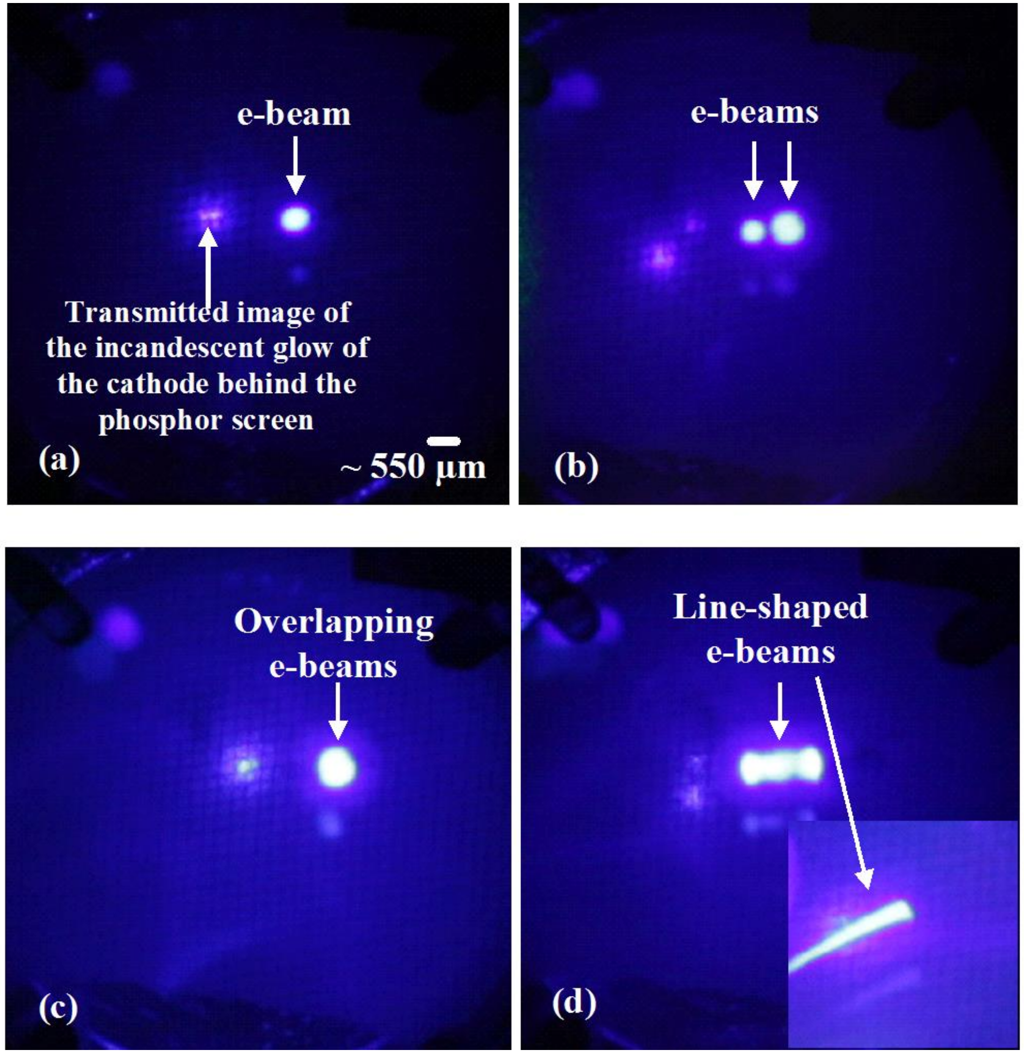
Schwede … Melosh … et al., Nature Materials 9, 762 (2010)



Vahdani Moghaddam, Yaghoobi, and Nojeh, 56th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN 2012), Waikoloa HI, USA (29 May – 01 June 2012)

Shaped and multiple electron beams

Due to the localized nature of heating, by shaping the laser beam, one can shape the electron beams, or create multiple beams. Might be useful for space-charge engineering?



Vahdani Moghaddam and Nojeh, 57th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN 2013), Nashville TN, USA (28-31 May 2013)

Heat Trap-based thermoelectrics?

Since we are maintaining very high temperatures in this solid material, perhaps we can make a Heat Trap-based thermoelectric, rather than thermionic, device? Then we won't need to get over the workfunction barrier. Our results on this are very preliminary at this point.

Thank you!

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A couple of review papers:

Nojeh, “Carbon nanotube electron sources: from electron beams to energy conversion and optophononics,” ISRN Nanomaterials, volume 2014, pages 879827-1 – 879827-23 (2014)

Khoshaman, Fan, Koch, Sawatzky, and Nojeh, “Thermionics thermoelectrics and nanotechnology: new possibilities for old ideas,” IEEE Nanotechnology Magazine, volume 8, pages 4-15 (2014)