OPTICAL RECTENNAS

# Nanotubes circumvent trade-offs

An optical rectenna made of a forest of multiwalled carbon nanotubes shows potential for direct conversion of light into d.c. electricity.

Garret Moddel

A rectenna is a combination of a rectifying diode and an antenna: the antenna picks up the electromagnetic radiation and converts it into an a.c current. The a.c. current flows through the diode, which rectifies it and produces d.c. power. Microwave rectennas have been used for half a century reaching power conversion efficiencies of over 80%. A rectenna that can similarly convert visible light into d.c current could be an innovative solar cell technology, but fundamental trade-offs due to a much higher operational frequency (up to 1 PHz) have thus far precluded any sort of practical energy conversion in the optical regime. Writing in *Nature Nanotechnology*, Baratunde Cola and co-workers at the Georgia Institute of Technology now report a carbon nanotube-based optical rectenna that shows potential to circumvent the key limitations of this technology[1].

The limited conversion efficiency at high frequencies is due to two conflicting factors: the *RC* time constant and impedance matching. Every electrical component has a capacitance (*C*) and a resistance (*R*) associated with it, such that the *RC* product determines how quickly a voltage across the device can change. To operate at anything close to 1 PHz the *RC* time constant must be tiny. For a metal/insulator/metal parallel-plate diode shown in Fig. 1a, the diode resistance ($R_D$) is inversely proportional to the area whereas its capacitance ($C_D$) varies directly with the area, so that $R_DC_D$ is independent of the plate area. The *RC* for the entire rectenna (antenna and diode) can be understood in terms of the simplified equivalent circuit shown in Fig. 1b (ref. 2). Here $R_D$ is effectively in parallel with the antenna resistance ($R_A$) so that when $R_A$ is much less than $R_D$, as in the device described by Cola and co-workers[1] the overall *RC* is approximately $R_AC_D$. This leads to the need for both $R_A$ and $C_D$ to be low. It would appear at first glance that making a diode with a very small area such that $C_D$ is small would be beneficial, but we need to take into account the second factor.

Impedance matching determines how much of the power received by the antenna couples to the diode. Looking again at the equivalent circuit in Fig. 1b, the optimal case would occur for $R_D = R_A$. The *RC* constraint therefore becomes that both $R_D$ and $C_D$ should be low. This is problematic since the product $R_DC_D$ is independent of the area and cannot be reduced by changing the diode size. The diode thickness and materials have some effect on these parameters, but it turns out that regardless of what dimensions and materials are chosen for a parallel-plate diode the *RC* can never be small enough to allow operation at optical frequencies[3].

To circumvent this fundamental constraint, researchers have investigated alternative geometries: making a diode with a sharp tip[4] or using a spatially distributed travelling-wave configuration[5] modifies the trade-off between low $R_D$ and low $C_D$; diodes that lie entirely in one plane greatly reduce the capacitance in tunnel diodes[6], nanochannel diodes[7] and geometric diodes[8]. Still, demonstration of a rectenna harvesting energy at optical frequencies has remained elusive.

To resolve this conundrum, Cola and co-workers use a miniature forest of multiwalled carbon nanotubes (Fig. 1c). Each nanotube acts as an antenna, picking up the incident radiation and converting it into a current. The nanotube is coated with an insulator and capped by a metal layer, forming a tiny tunnel diode. Because the

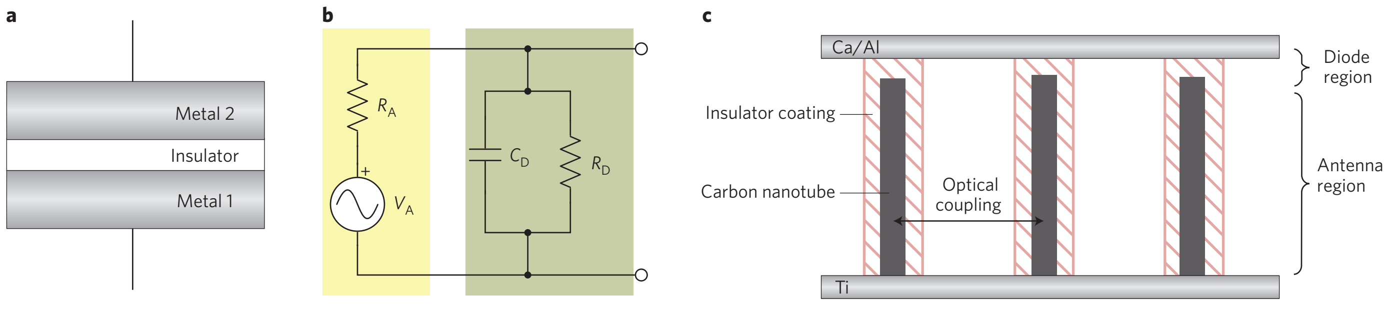


**Figure 1 |** A rectenna diode. **a**, A metal–insulator–metal diode: a thin insulator is sandwiched between two metal electrodes. Because the capacitance ($C_D$) of the device varies with the area and the resistance ($R_D$) varies with the reciprocal of the area, it is impossible for such a diode to respond at optical frequencies. **b**, The *RC* for the entire rectenna can be obtained using a simplified equivalent circuit. The antenna is represented by the series resistor ($R_A$) and voltage source shown in the yellow shaded region, and the diode is represented by the parallel capacitance ($C_D$) and resistor ($R_D$) shown in the green shaded region. Light incident on the antenna produces an oscillating voltage, $V_A$, and the diode rectifies the oscillating signal to produce a d.c output at the two terminals on the right. **c**, Schematic of the carbon nanotube optical rectenna. Multiwalled carbon nanotubes, at high density, are grown on a metal-coated substrate, coated with an insulator, and capped with a second metal coating, which forms a diode at the upper contact. The nanotubes act as an antenna, converting the incident light into alternating current that is transferred to the diodes, where it is converted into d.c electrical power. For efficient power coupling from the antenna, $R_D$ must be approximately equal to $R_A$, which is far from the case for multiwalled carbon nanotube rectennas — yet the devices work well, because optical coupling between the high density of nanotubes provides many opportunities for the incoming light power to couple into a diode.

area of the tip is minute, with a diameter of approximately 10 nm, the diode capacitance $C_D$ is very small, whereas the antenna resistance $R_A$ is expected to be approximately 100 Ω. The resulting $R_AC_D$ product remains small enough to allow optical frequency rectification. So far, so good.

Because the diode area is minute, the diode resistance $R_D$ is huge. A problem arises from the vast difference between the diode resistance and the antenna resistance. Because of the terrible impedance matching only a miniscule fraction of the power incident on the antenna couples to the diode. For most rectennas this would be disastrous to the conversion efficiency, because the incident power that is not transferred to the diode would be lost in the form of radiation bouncing off the device, and possibly heating the antenna.

This is where the special characteristics of the closely spaced forest of nanotubes come into play. Each carbon nanotube is optically coupled to its neighbours[9], such that the power that is rejected from one diode is coupled to neighbouring ones. Even though the coupling between each antenna–diode pair is poor, with a density of $10^{10}$ carbon nanotubes per $cm^2$, there are ample opportunities for the power to be coupled to another diode. In this way, it is possible that this carbon nanotube optical rectenna circumvents what appeared to be an unworkable trade-off between the *RC* time constant and efficient antenna–diode coupling.

If replication of Cola and colleagues' work proves that multiwalled carbon nanotubes can in fact be used to achieve efficient energy harvesting with optical rectennas, this nanotechnology could become appealing for practical applications. However, much more work remains to be done to improve the diodes for efficient rectification, as well as to develop low-cost fabrication techniques for multiwalled carbon nanotubes suitable for reliable device applications. ❐

*Garret Moddel is in the Department of Electrical, Computer, and Energy Engineering at the University of Colorado, Boulder, Colorado 80309-0425, USA.*
*e-mail: moddel@colorado.edu*

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