and protective shell. The nanoscale and hydrophobic structures of the network enable the otherwise water-absorbing cotton to repel water nearly as efficiently as the lotus leaf. Furthermore, the treated fabrics are stronger and more resistant to tears. Nanotube concentrations of over 2% in the applied emulsion made it more difficult for the cloth to catch fire and prevented burning by forming a carbonaceous amorphous char on the surface of the cotton, which behaved as a heat shield. With just 0.25% of nanotubes, more than 90% of the harmful ultraviolet rays that would normally penetrate an untreated fabric could be blocked.

Strong fabrics with ultraviolet resistance and water-repellent properties may offer new alternatives to soft linings in marine and outdoor applications. Furthermore, cotton fabrics coated with nanotubes that are modified with enzymes capable of detecting and detoxifying chemical warfare agents could offer a new line of comfortable chemical protective clothing for the military and civilian first responders[3]. Textiles coated with nanotubes modified with other enzymes may also be used to make drug-impregnated gloves for arthritic patients or be used as a bed lining for transdermal drug delivery while a person sleeps on it.

The reported results are impressive and future studies using highly pure nanotubes with a specific set of well-characterized electrical, chemical and physical properties will offer a myriad of tailor-made applications. If the electronic properties of the nanotubes on the surface of the cotton can be harnessed, it will be possible to design wearable sensors or to build power generators and energy storage capabilities into the clothing.

For example, the piezoresistance properties of nanotubes may be used to detect variations of electrical conductance as a function of mechanical deformation of the fabrics. This could be used to monitor the motion of muscles and limbs for rehabilitative and telemedicine applications. Because chirality (or handedness) of nanotubes defines whether they are metallic or semiconducting, it is possible to engineer fabrics that are either insulating or conducting.

If a single layer of nanotubes can be deposited around the cotton fibre, the configuration of an insulating fibre located directly underneath a conductive layer may be exploited to fabricate flexible transistors[4]. Multilayering, on the other hand, may allow high rates of conduction with low rates of heat dissipation, making low-power wearable electronics a closer reality[5].

The reported results are of great interest and further studies are needed to understand the mechanisms responsible for the improved properties. The synergy between a flexible renewable natural substrate such as cotton and the increasing multifunctionality of nanotubes offers an endless number of possibilities. Perhaps one day it will allow us to dress like superheroes.

References

1. http://www.cotton.org
2. Liu, Y., Wang, X., Qi, K. & Xin, J. H. *J. Mater. Chem.* doi: 10.1039/b801849a (2008).
3. Wang, J. Timchalk, C. & Lin, Y. *Env. Sci. Technol.* **42,** 2688–2693 (2008).
4. Maccioni, M., Orgiu, E., Cosseddu, P., Locci, S. & Bonfiglio, A. *Appl. Phys. Lett.* **89,** 143515–143518 (2006).
5. Hyde, G. K., Park, K. J., Stewart, S. M., Hinestroza, J. P. & Parsons, G. N. *Langmuir* **23,** 9844–9849 (2007).

INSTRUMENTATION

Astronomers look to nanotechnology

A superconducting detector can count photons and measure their energy with an accuracy that could be good enough for space-based far-infrared telescopes.

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Astronomers are greedy: they want to capture as much light as possible and extract every possible piece of information from even the faintest signal. A new detector[1] developed by researchers in the US now offers the possibility of unprecedented sensitivity at far-infrared wavelengths — a region of the electromagnetic spectrum that contains a wealth of information about the most-distant, and therefore the oldest, objects in the universe. This region of the spectrum has remained painfully elusive for astronomy to date, but a number of space-based telescopes, such as those of the SAFIR mission[2,3], are now being planned to explore the formation of galaxies, stars and planetary systems at far-infrared wavelengths.

Light from the most distant reaches of the universe is best detected in the far-infrared region, which runs from about 100 μm to 1 mm, because visible light is typically obscured by dust clouds in space. However, far-infrared light is absorbed by the Earth's atmosphere, which means that the most sensitive telescopes observing at these wavelengths need to be based in space. Another challenge is that far-infrared signals tend to be very weak, even by astronomical standards, because they have travelled extremely long distances.

Advances in far-infrared astronomy therefore depend on the development of much more sensitive detectors for photons at these wavelengths. On page 496, Michael Gershenson, Boris Karasik and co-workers[1] at Rutgers University, the Jet Propulsion Laboratory and the State University of New York at Buffalo combine recent advances in nanolithography, low-temperature physics and quantum detectors to make a bolometer — a device that can measure the energy of photons — that might offer the level of performance needed to detect single far-infrared photons.

For a century, ever since Einstein explained the photoelectric effect, it has been known that light comes in packets known as photons. The visible region of the spectrum runs from about 700 nm (red photons with energies ~1.6 eV) to about 400 nm (violet photons with energies ~3.0 eV). We do not experience the photon aspect of visible light in our everyday lives, but the quantum nature of radiation at X-ray wavelengths — where the photons have energies of 1,000 eV or higher — can be heard in the clicks of a Geiger counter, with each click corresponding to the absorption of an X-ray photon.

In a Geiger counter, every X-ray photon liberates a photoelectron, producing an electrical cascade that is then converted into a click. Modern solid-state detectors

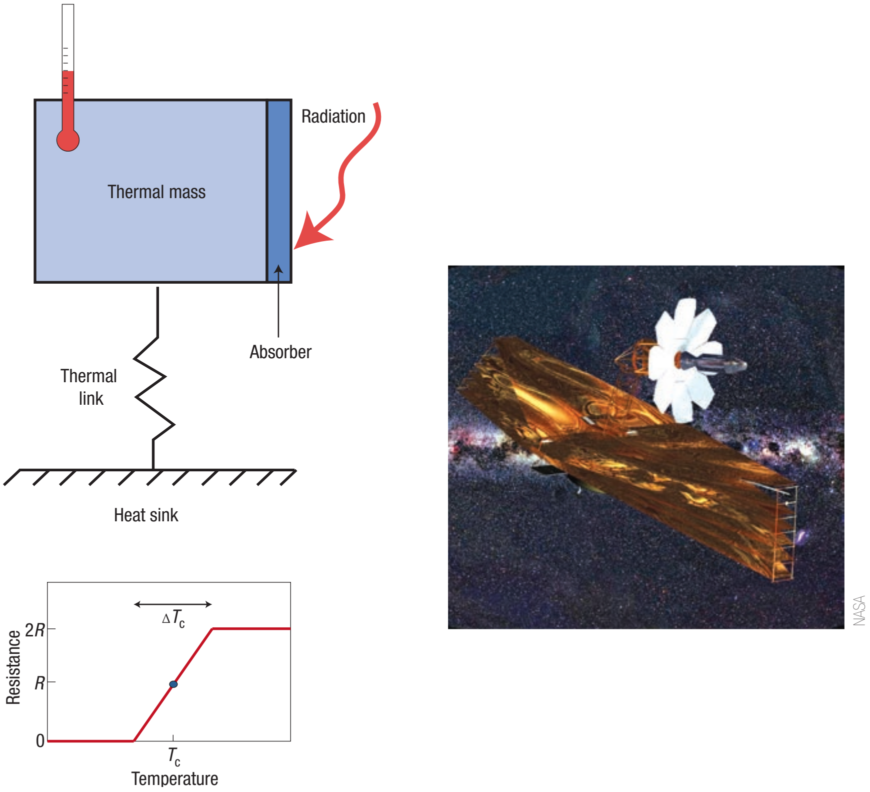

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Figure 1 Schematic diagram (top left) showing the main elements of a bolometer: an absorber, which converts light into heat; a thermal mass with a small heat capacity, which results in large temperature changes; a thermometer, which detects these temperature changes; and a thermal link, which allows the heat to drain away to the heat sink. In the hot-electron nanobolometer built by Gershenson, Karasik and co-workers[1], the electrons in the titanium nanowire act as all these elements, which ensures maximal efficiency of operation. The resistance of the nanowire (bottom left) falls from its normal value (2R) to zero over a small temperature range, ΔT_c, around the superconducting transition temperature, T_c. Measuring this resistance allows the temperature, and hence the energy of each individual photon, to be measured. Such a detector might be used on the Single Aperture Far Infrared Observatory (SAFIR; right) that is planned by NASA for future decades. SAFIR would have a 10-metre reflecting collector, cooled to 4 K, to direct the far-infrared photons onto the detector array. The reflector is large and will open like a flower, as shown. An even larger cooled sunshield below the petal-like segmented mirror will be used to prevent far-infrared photons from the sun reaching the telescope.

known as avalanche photodiodes can record individual visible and near-infrared photons at room temperature, but much colder detectors are needed to record far-infrared photons, which have energies that are about 100–1,000 times smaller than those of visible photons. It is even more challenging to measure the energy of each absorbed photon.

Cryogenic detectors operate on one of two basic principles. The initial photoelectron creates either electrical excitations (which are collected and amplified, as in an avalanche photodiode) or thermal excitations, as in the nanobolometer built by Gershenson, Karasik and co-workers[1]. In this device the far-infrared photon is absorbed by a superconducting titanium nanowire. The nanowire is held within a specific temperature region over which the resistance drops from its normal value to zero (Fig. 1). The temperature of the electrons, and thus the resistance of the nanowire, increases briefly after absorption of the photon. This is the hot-electron aspect of the detector. If the photons arrive continuously in rapid succession, the temperature and resistance increases to a new, relatively steady value. If the photon arrival rate is low, on the other hand, the temperature and resistance rise as each photon is absorbed, and then fall back to the resting value.

The first cryogenic single-photon detectors developed for astronomy were silicon devices that recorded both the energy and the arrival rate of X-ray photons[4]. The same principle, using superconducting microwires instead of a semiconductor, has been used to detect visible photons[5]. However, to detect single far-infrared photons, the volume of the wire must be much smaller — hence the use of nanowires by the Rutgers–JPL–Buffalo team — and its thermal isolation from the environment must be implemented even more rigorously. This is done by making the contacts to the titanium nanowire from a different superconducting metal — niobium in this case — which has a higher transition temperature and therefore remains superconducting throughout the experiments. The interface between the titanium and the niobium prevents heat flowing out of the nanowire, thus ensuring effective thermal isolation. The heat from the photon(s) can escape only when the warmer electrons emit lattice vibrations known as phonons. This is a relatively slow process, which limits the temporal resolution, but it also leads to a more sensitive detector. The small volume of the nanowire further increases the sensitivity. A superconducting quantum interference device (SQUID) is used to read the resistance of the nanowire. This approach, which is also used in the microwire detectors for visible photons, is capable of handling thousands of detectors simultaneously, thus allowing images containing thousands of pixels to be recorded.

Gershenson, Karasik and co-workers have shown that the amount of heating in their devices, and also the timescale for resetting the nanowire temperature, are in line with expectations, although these tests have only been performed with low-frequency heating and near-infrared photons, which have much higher energies than their far-infrared counterparts. However, on the basis of results to date, the projected performance with far-infrared photons should be able to meet the specifications envisioned for the SAFIR mission. This is expected to involve being able to detect individual far-infrared photons at arrival rates of up to 10,000 photons per second, and to measure the energy of each photon to maybe 10% accuracy. This hot-electron nanobolometer demonstrates that we should soon have detectors that will 'click' for photons with energies that are 1,000 times smaller than those of visible photons and measure the energy of each photon. Einstein would be proud, but probably not surprised. Astronomers should be very pleased.

References

1. Wei, J. *et al. Nature Nanotech.* **3,** 496–500 (2008).
2. Benford, D. J. & Moseley, S. H. *Nucl. Inst. Meth. A* **520,** 379–381 (2004).
3. http://safir.jpl.nasa.gov/
4. Moseley, S. H., Mather, J. C & McCammon, D. *J. Appl. Phys.* **56,** 1257–1262 (1984).
5. Irwin, K. D. *Sci. Am.* **295,** 86–92 (November 2006).