regime from visible to infrared because the light-to-heat conversion process is not limited by a cutoff wavelength. The efficiency is comparable to that of state-of-art bolometers. The response speed can be almost 100 times higher than conventional TE detectors (thermopiles), because the resonant TE photodetector is much smaller in size. Lastly, the device offers built-in spectral selectivity, since the resonant absorption of the nanowire is narrow-band and can be configured to any wavelength through structural changes. In comparison, conventional photodetectors have to rely on colour filters for spectral selectivity.

Undeniably, though, there are still challenges to overcome before this technology is ready for practical applications. Although it can be made to operate at any wavelength, realizing broadband detection in a single device will be difficult because it relies on an optical resonance to generate and localize heat. In addition, while the efficiency of individual detectors is high, the total efficiency of the photodetector chip is still low, owing to a low filling factor of the photoactive region. Despite these challenges, the resonant TE nanophotonic platform proposed by Mauser *et al.* can be optimized for efficiency and speed, for example by increasing the optical cross section and reducing the junction volume.

It is usually thought that heat, with its high entropy, should be avoided when converting electromagnetic energy into electricity. In recent years, however, this idea has been challenged by the progress made in thermophotonic applications. In addition to the TE photodetector presented by Mauser *et al.*, other notable examples include thermophotovoltaic cells[3] and hot-carrier photodetectors[4]. In these cases, heat is the intermediate stage during energy conversion. By first converting light to heat, it is possible to overcome the fundamental bandgap limitation of semiconductor-based technologies. As new challenges arise in converting heat to electricity, sophisticated thermophotonic designs are expected to play an increasingly important role in advancing this technology. ❐

Ming Zhou and Zongfu Yu are in the Department of Electrical and Computer Engineering, University of Wisconsin – Madison, Madison, Wisconsin 53706, USA.
e-mail: zyu54@wisc.edu

References

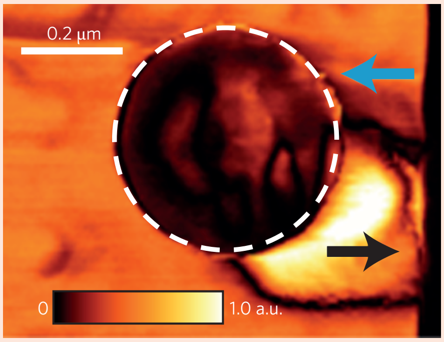
1. Mauser, K. W. *et al. Nat. Nanotech.* **12,** 770–775 (2017).
2. Cao, L. *et al. Nat. Mater.* **8,** 643–647 (2009).
3. Lenert, A. *et al. Nat. Nanotech.* **9,** 126–130 (2014).
4. Gabor, N. M. *et al. Science* **334,** 648–652 (2011).

FERROELECTRIC MATERIALS

Walls and memory

A domain in a ferroic phase, for example a ferroelectric or a ferromagnetic one, is a well-defined spatial region containing a long-range-ordered configuration for the relevant local order parameter — the ordered electric dipole or magnetic moment for the two examples above, respectively. Different domains are distinguishable because of a different spatial orientation for the order parameter.

Most of the current research on the applications of ferroic materials focuses on the boundaries between neighbouring domains, also known as domain walls, because of their remarkable functional properties. As a prime example, the electrical conductivity value is finite along specific types of domain walls in ferroelectric materials despite the vanishing value inside the domain. There have been various proposals for using domain walls as active elements in electronic devices and, in particular, non-volatile memories. However, in spite of several advances in the manipulation of the ferroelectric domain walls and in the control of their conductivity, proof-of-principle working memory devices are still missing.



AAAS

Writing in *Science Advances* (**3,** e1700512; 2017), Pankaj Sharma *et al.* now report on a prototype two-terminal device based on reconfigurable ferroelectric domain walls and acting as non-volatile resistive memory. The researchers use high-quality epitaxial (110)-oriented $BiFeO_3$ thin films, exploiting their well-known exceptional uniformity — that is, virtually no domains are observed in as-grown samples — and pattern asymmetric coplanar Pt/Ti electrodes on the $BiFeO_3$ surface. Acting with the tip of a conductive atomic force microscope on one electrode generates in-plane electric fields which, in turn, lead to the generation — or successive deletion — of a pair of ferroelectric domain walls, as visualized by means of piezoresponse force microscopy. The image shows a mapping of the piezoresponsive signal in false colours. Domain walls are imaged as black lines bridging the electrodes, that is, the central dark circle and the dark stripe on the right-hand side, while the arrows denote the local direction of the electrical polarization. To generate and delete domain walls, voltage values around 8 V are required.

Once the walls are generated, the researchers perform a non-destructive, low voltage current mapping of the device by means of conductive atomic force microscopy, confirming a substantial electrical conductivity through the domain walls but negligible contributions through the domain bulk. As a result, confirmed over ~10^3 cycles, conductive bridges between the two electrodes lead to a low resistance ON state, while a high-resistance OFF state is obtained in the absence of domain walls — the characteristic resistance values differing by more than three orders of magnitude. The researchers further demonstrate that the characteristic electrical conductivity value in the ON state can be tuned by varying the distance between the electrodes and, accordingly, the characteristic length of domain walls. Specifically, longer domain walls are characterized by lower conductivity values. These observations demonstrate potential prospects of multilevel data storage going beyond the binary ON/OFF operation.

GIACOMO PRANDO