Nanoscale thermal imaging of dissipation in quantum systems.

D. Halbertal, J. Cuppens, M. Ben Shalom, L. Embon, N. Shadmi, Y. Anahory, H. R. Naren, J. Sarkar, A. Uri, Y. Ronen, Y. Myasoedov, L. S. Levitov, E. Joselevich, A. K. Geim, and E. Zeldov.

arXiv: 1609.01487

Recommended with a commentary by Bertrand I. Halperin, Harvard University

Thermal imaging is a technique with an enormous range of applications, on every conceivable length scale. On the largest length scales, we may include measurements of small anisotropies in the cosmic microwave background radiation, and on the human length scale, we may include measurements of heat leakage from houses in the winter, or maps of skin temperature for medical purposes. The paper by Halbertal, *et al*. describes an innovative technique, developed in the laboratory of Eli Zeldov at the Weizmann Institute of Science, for imaging heat dissipation in low temperature quantum systems, and demonstrates the power of the technique by using it to study entropy production at 4.2K in several structures of interest.

The temperature sensor developed for these experiments employs a superconducting quantum interferometer (SQUID), of order 50 nm diameter, formed at the tip of a drawn glass pipette, mounted on a scanning device. The authors report sensitivities below 1 μK/$Hz^{1/2}$, which they say is four orders of magnitude better than previous thermal imaging devices. They can detect nanoscale dissipation as small as 40 fW, which is the scale of the fundamental minimum heat production for a single qubit operating at 1 GHz at 4K.

Given a thermometer of the desired size and sensitivity, there still remains the question of how to use it to measure the local temperature of a sample. How should one transfer heat to the thermometer, with reasonable efficiency, from a localized source in the sample, at helium temperatures? Heat transfer by electromagnetic radiation is negligible at these temperatures, but Zeldov's group solves the problem by admitting several mbar of ^{4}He gas into the sample chamber. At this pressure, the mean-free-path of the He atoms is large compared to the distances involved, so energy is transported ballistically from the sample to the thermometer.

The thermometer is designed so that the thermal resistance R_{ss} between the SQUID sensor and its supporting structure is large compared to the effective thermal resistance R_{sd} for heat transfer between the device being studied and the SQUID. Consequently, the temperature of the sensor should be equal to that of the measured device, averaged over the sensitive area below the tip. This area is determined, roughly, by the lesser of the diameter of the SQUID and its height above the sample. At the same time, R_{sd} is designed to be large compared to the thermal resistance R_{db} between the device being studied and the substrate it sits on, so that the thermometer can be a non-invasive probe of the temperature distribution in the device. Since the helium gas is sensitive to the lattice temperature but not the electron temperature, locations of increased temperature are indicative of places where the energy of hot electrons is converted to phonons.

Heat production can be measured in a mode where a dc current is run through the sample, so that a time-independent temperature profile is reached, or one can run an ac current, at frequency f, through the sample, and measure the temperature variation at the harmonic frequency $2f$. (Frequencies up to several hundred kHz were used in the reported experiments.) The ac mode enhances sensitivity and spatial resolution, in many situations. An ac current through the device will also produce a fluctuating magnetic field at frequency f, which may be detected if the SQUID is operated in a regime where it is sensitive to local magnetic field variations as well as to temperature.

The sensor may also be used in a mode that can enhance contrast by measuring the gradient of the temperature along a specified axis. This was accomplished by attaching the sensor to the tip of a vibrating tuning fork and measuring temperature fluctuations at the frequency of the fork. Still another mode of operation is an ac scanning gate mode, where an ac voltage is applied to the sensor tip, strong enough to perturb the sample by electrostatic interaction, and the induced temperature variation is detected by the sensor.

Even when the scanning tip is at zero voltage relative to the sample, the tip will perturb the sample due to the difference in work functions. Thus, in normal operation, the sensor will act as a dc scanning gate, and the measured signal will contain a component induced by the gate in addition to the temperature rise that would have been there without it. The perturbation of the tip may be increased or decreased by varying the voltage on the tip, so the induced component can be separated from the unperturbed temperature rise.

The authors' study of dissipation in two current-carrying single-wall carbon nanotubes provides one impressive illustration of the power of the imaging technique. The attached figure shows results from the nanotubes, whose geometries are shown in the SEM images of panels *d* and *e*. Panels *a* and *b* are ac thermal images, showing the amplitude $T_{ac}(x,y)$ of temperature variation when an ac current of 12 nA (*a*) or 3 nA (*b*) is sent through the samples. The image in *b* shows that there is a short at the point where the nanowire crosses itself, so that the lower loop carries no current.

Close analysis of the images in panels *a* and *b* reveals that the phonon heat production may be enhanced at isolated spots in the nanotube, which the authors argue are sites of localized electronic states that have become resonant with the Fermi level due to the scanning gate effect. Panel *c* shows a zoom-in on the ac temperature map around the point labeled 2*c* in the SEM image *d*. The authors propose that the concentric rings are centered about a localized state, which is brought in an out of resonance by the dc potential of the tip, as it is scanned above the surface. This interpretation is supported by the fact that radii of the rings depend, as expected on the height of the tip and the voltage on it. Panel *f* is a line cut across the rings, showing a separation of 20 nm between the maximum and minimum of dissipation. The resolution with which one can locate the position of the defect is presumably better than that.

In other examples of the power of their instrument, the authors present thermal images of local heating in a graphene device, revealing resonant dissipative states at the edges, and a zig-zag chain of alternating copper and permalloy nanowires, showing higher local dissipation in the more resistive permalloy. The authors show that their sensor will work well at temperatures up to 7K and they note that their technique should also work at temperatures from tens of K down to tens of mK, if one uses a superconductor with an appropriate critical temperature and uses an appropriate heat transfer medium, such as ^{3}He gas, liquid ^{3}He, or ^{3}He dissolved in liquid ^{4}He. The technique therefore opens an exciting possibility to observe and understand dissipative processes arising from nanoscale defects in a wide variety of interesting devices.

.

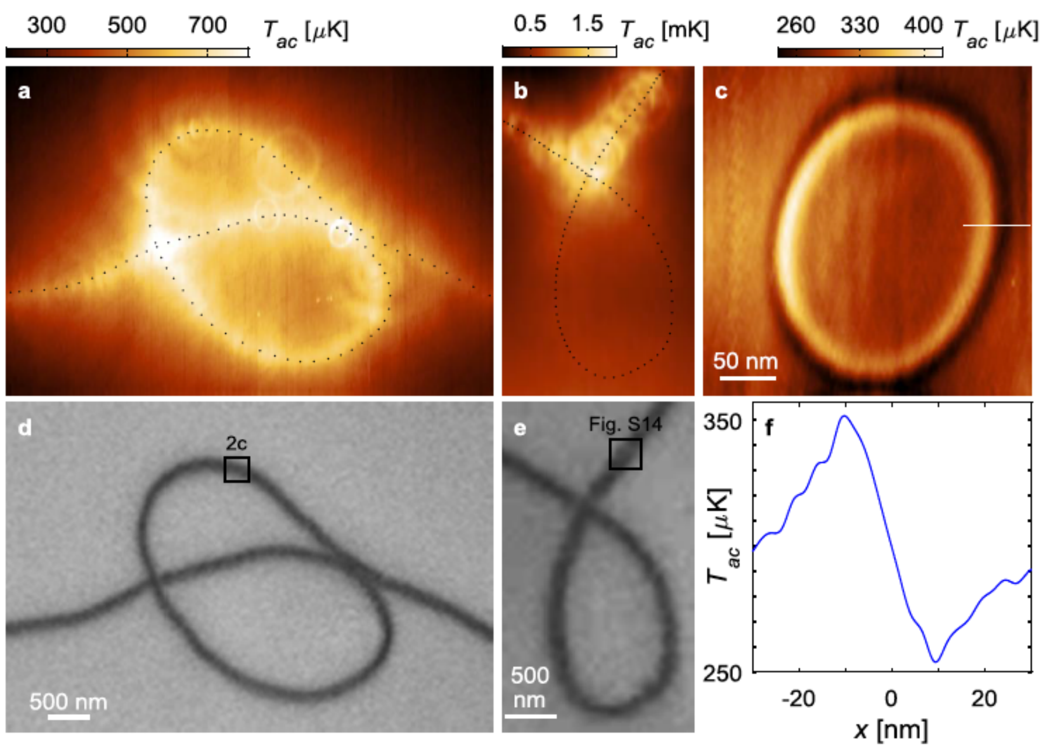

Figure Caption. Thermal imaging of two current-carrying carbon tubes. See text for explanations.