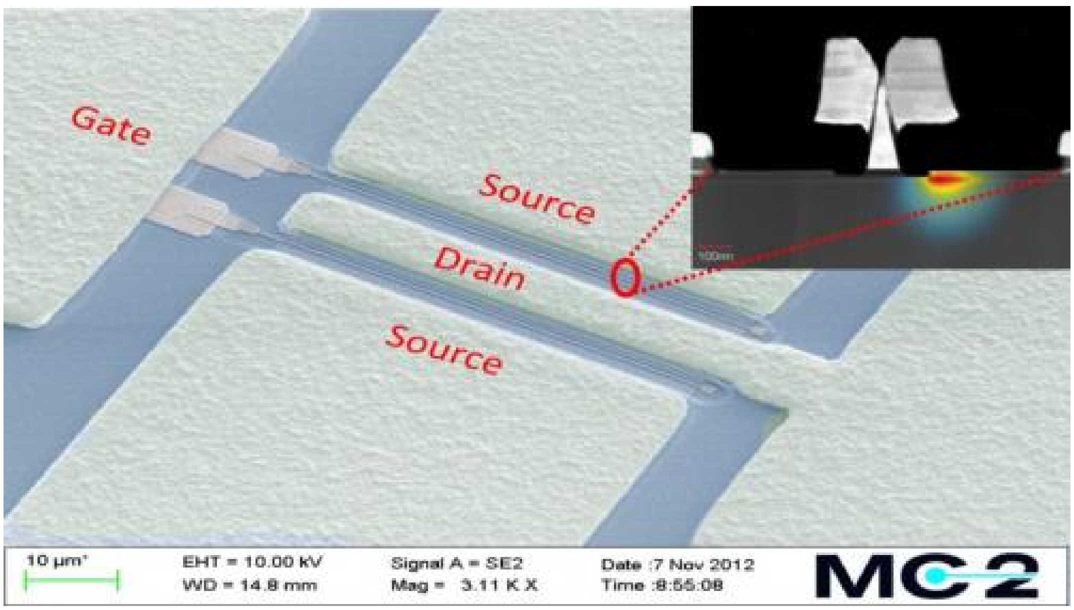
Heat transfer sets the noise floor for ultrasensitive electronics

November 10 2014, by Ker Than



An electron microscope image of an indium phosphide high electron mobility transistor (InP HEMT). The region affected by the self-heating process is highlighted in the cross section of the InP HEMT. Credit: Chalmers University of Technology

A team of engineers and scientists has identified a source of electronic noise that could affect the functioning of instruments operating at very low temperatures, such as devices used in radio telescopes and advanced physics experiments.

The findings, detailed in the November 10 issue of the journal *Nature*

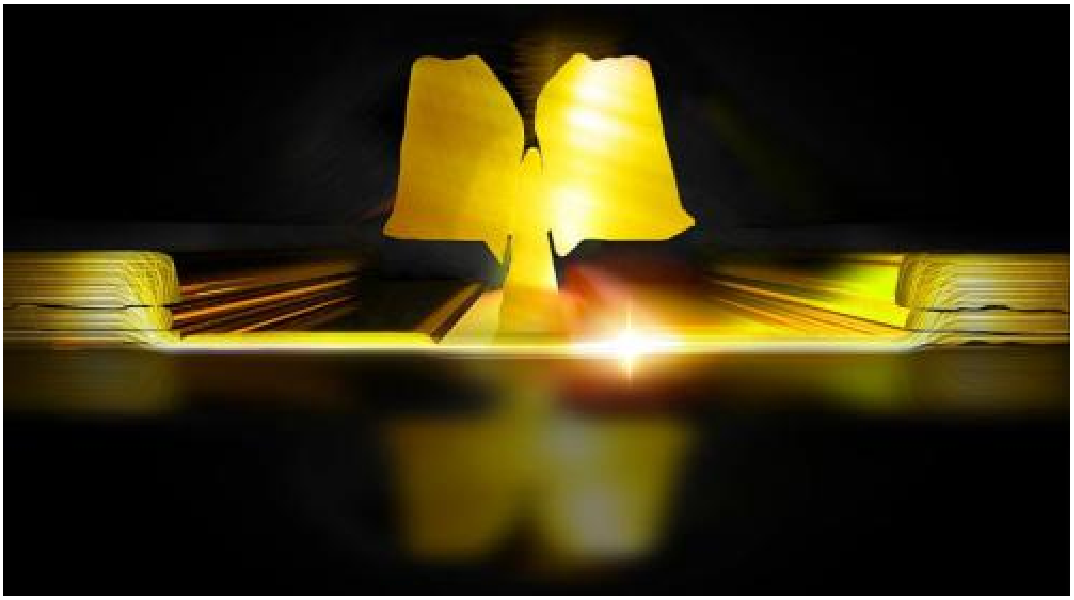
Materials, could have implications for the future design of transistors and other electronic components.

The electronic noise the team identified is related to the temperature of the electrons in a given device, which in turn is governed by heat transfer due to packets of vibrational energy, called phonons, that are present in all crystals. "A phonon is similar to a photon, which is a discrete packet of light," says Austin Minnich, an assistant professor of mechanical engineering and applied physics in Caltech's Division of Engineering and Applied Science and corresponding author of the new paper. "In many crystals, from ordinary table salt to the indium phosphide crystals used to make transistors, heat is carried mostly by phonons."

Phonons are important for electronics because they help carry away the thermal energy that is injected into devices in the form of electrons. How swiftly and efficiently phonons ferry away heat is partly dependent on the temperature at which the device is operated: at high temperatures, phonons collide with one another and with imperfections in the crystal in a phenomenon called scattering, and this creates phonon traffic jams that result in a temperature rise.

One way that engineers have traditionally reduced phonon scattering is to use high-quality materials that contain as few defects as possible. "The fewer defects you have, the fewer 'road blocks' there are for the moving phonons," Minnich says.

A more common solution, however, is to operate electronics in extremely cold conditions because scattering drops off dramatically when the temperature dips below about 50 kelvins, or about -370 degrees Fahrenheit. "As a result, the main strategy for reducing noise is to operate the devices at colder and colder temperatures," Minnich says.



A cross sectional image of an ultra-low noise transistor. Electrons, accelerated in the high mobility channel under the 100 nanometer gate, collide and dissipate heat that fundamentally limits the noise performance of the transistor. Credit: Lisa Kinnerud and Moa Carlsson, Krantz NanoArt

But the new findings by Minnich's team suggest that while this strategy is effective, another phonon transfer mechanism comes into play at extremely low temperatures and severely restricts the heat transfer away from a device.

Using a combination of computer simulations and real-world experiments, Minnich and his team showed that at around 20 kelvins, or -424 degrees Fahrenheit, the high-energy phonons that are most efficient at transporting heat away quickly are unlikely to be present in a crystal. "At 20 kelvins, many phonon modes become deactivated, and the crystal has only low-energy phonons that don't have enough energy to carry away the heat," Minnich says. "As a result, the transistor heats up until the temperature has increased enough that high-energy phonons become available again."

As an analogy, Minnich says to imagine an object that is heated until it is white hot. "When something is white hot, the full spectrum of photons, from red to blue, contribute to the heat transfer, and we know from everyday experience that something white hot is extremely hot," he says. "When something is not as hot it glows red, and in this case heat is only carried by red photons with low energy. The physics for phonons is exactly the same—even the equations are the same."

The electronic noise that the team identified has been known about for many years, but until now it was not thought to play an important role at low temperatures. That discovery happened because of a chance encounter between Minnich and Joel Schleeh, a postdoctoral scholar from Chalmers University of Technology in Sweden and first author of the new study, who was at Caltech visiting the lab of Sander Weinreb, a senior faculty associate in electrical engineering.

Schleeh had noticed that the noise he was measuring in an amplifier was higher than what theory predicted. Schleeh mentioned the problem to Weinreb, and Weinreb recommended he connect with Minnich, whose lab studies heat transfer by phonons. "At another university, I don't think I would have had this chance," Minnich says. "Neither of us would have had the chance to interact like we did here. Caltech is a small campus, so when you talk to someone, almost by definition they're outside of your field."

The pair's findings could have implications for numerous fields of science that rely on superchilled instruments to make sensitive measurements. "In radio astronomy, you're trying to detect very weak electromagnetic waves from space, so you need the lowest noise possible," Minnich says.

Electronic noise poses a similar problem for quantum-physics experiments. "Here at Caltech, we have physicists trying to observe certain quantum-physics effects. The signal that they're looking for is very tiny, and it's essential to use the lowest-noise electronics possible," Minnich says.

The news is not all gloomy, however, because the team's findings also suggest that it may be possible to develop engineering strategies to make phonon heat transfer more efficient at low temperatures. For example, one possibility might be to change the design of transistors so that phonon generation takes place over a broader volume. "If you can make the phonon generation more spread out, then in principle you could reduce the temperature rise that occurs," Minnich says.

"We don't know what the precise strategy will be yet, but now we know the direction we should be going. That's an improvement."

More information: The study "Phonon black-body radiation limit for heat dissipation in electronics" is published in *Nature Materials* on November 10th: dx.doi.org/10.1038/nmat4126

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