Researchers build a quantum dot energy harvester

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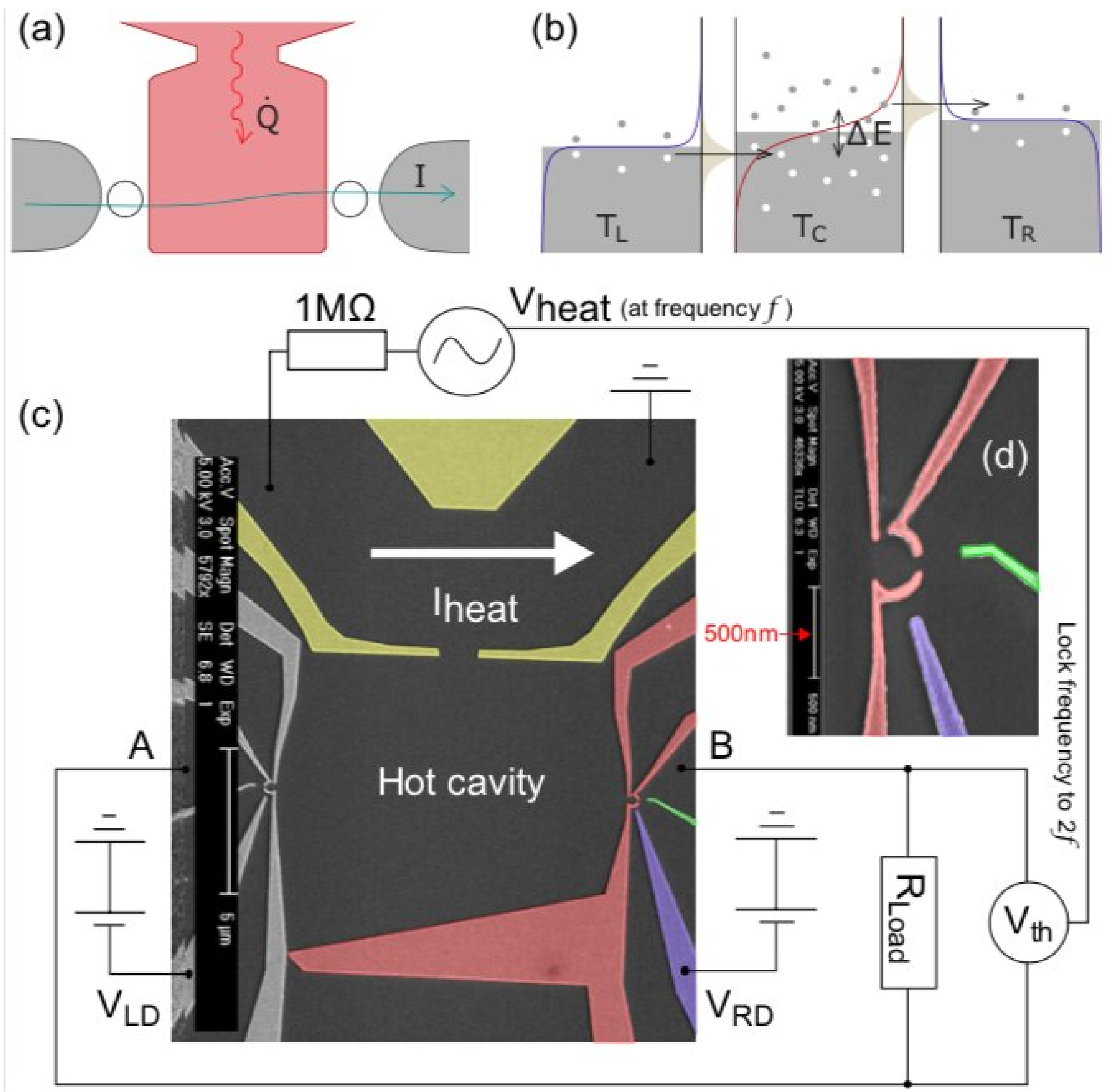


Credit: Jaliel et al.

Over the past few years, thermoelectric generators have become the focus of a growing number of studies, due to their ability to convert waste heat into electrical energy. Quantum dots, semiconductor crystals with distinctive conductive properties, could be good candidates for thermoelectric generation, as their discrete resonant levels provide excellent energy filters.

In a recent study, researchers at the University of Cambridge, in collaboration with colleagues in Madrid, Rochester, Duisburg and Sheffield, have experimentally demonstrated the potential of an autonomous nanoscale energy harvester based on resonant tunneling quantum dots. This harvester is based on previous research carried out by part of their team, who had proposed a three-terminal energy harvester based on two resonant-tunneling quantum dots with different energy levels.

The energy harvester device was realized at Cavendish Laboratory in Cambridge by a researcher called Gulzat Jaliel. The original theoretical proposal for the device, however, was introduced by Andrew Jordan in 2013, and the theoretical work behind the harvester was carried out by him in collaboration with renowned semiconductor physicist Markus Büttiker and a team of post-doctoral students in Geneva.

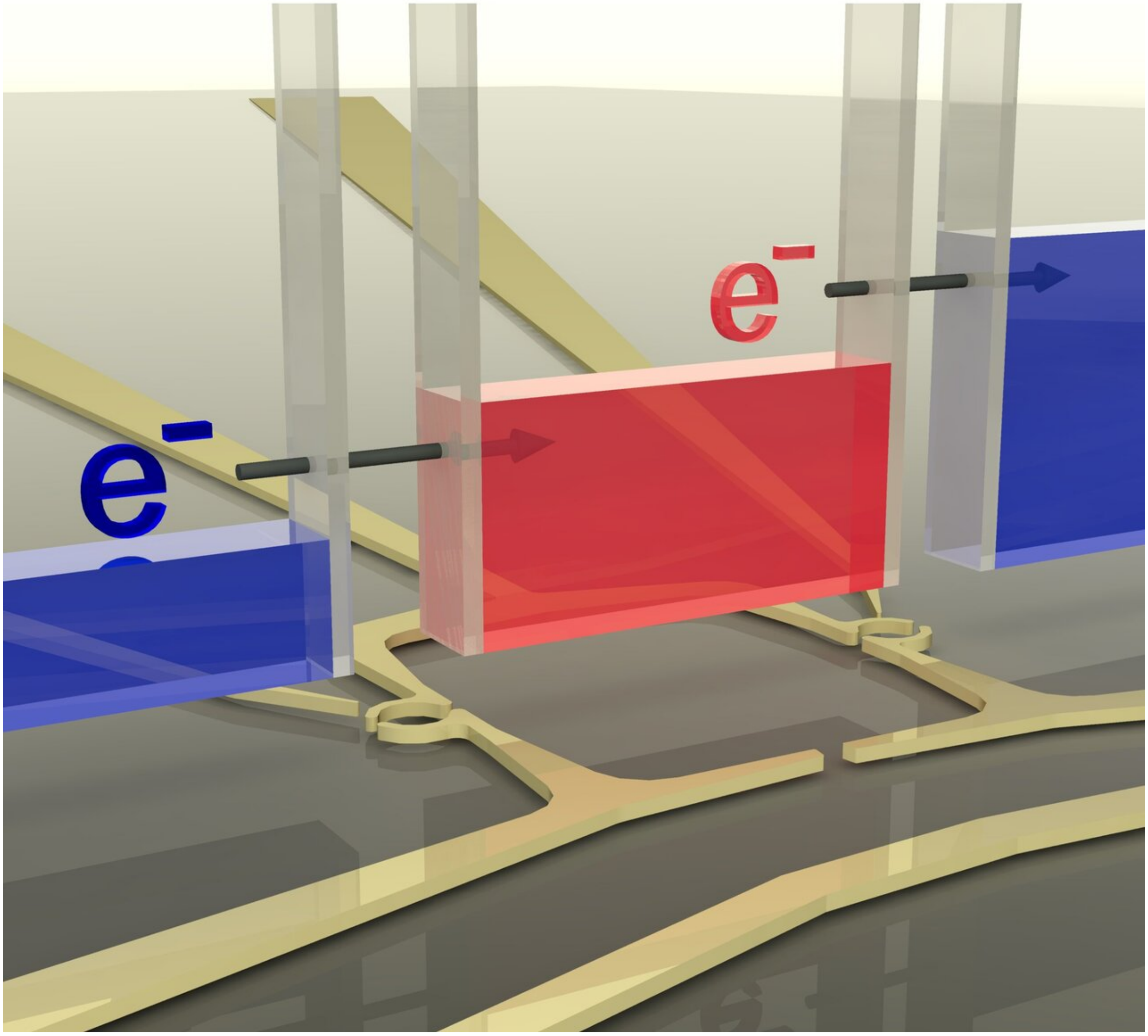
"Since the paper by my colleagues Rafa and Markus on Coulomb blockaded dots, I started thinking about thermoelectrics in mesoscopic circuits," Jordan, one of the researchers who developed the theory behind the harvester, told Phys.org. "During my sabbatical in Geneva in 2010-2011, we were thinking and calculating about the chaotic cavity thermal engine with quantum point contacts and I ended up publishing another paper with Björn and Rafa."

The device previously proposed by Jordan and some of his colleagues, however, predicted a low power. In the summer of 2013, therefore, when he went back to Geneva for a brief visit, Jordan started exploring the relation between resonant tunneling and thermoelectricity further. His intuition was that a device that utilizes resonant quantum dots would have larger power and high efficiency.

"I remember very well sitting in my hotel room on a Saturday in Geneva, playing with the equations, and realizing that if we simply gave the cavity its own temperature and chemical potential, then everything became very simple and we had a nice result that for every interval of energy the electron picked up, a single electron charge was transported and the charge and energy balance was simple," Jordan said. "Scaling up would also be simple, in principle. I wrote the results up with Björn and Rafa, and Markus, of course, and the rest is history."

The recent study kicked off when Jaliel's Ph.D. supervisor, Prof. Charles G. Smith, advised her to try to attempt the experimental realization of the quantum dot energy harvester as part of her thesis and she decided to give it a try. Her project was also inspired by previous research carried out by Dr. Jonathan Prance at the Cavendish Laboratory, in which he used a similar device to demonstrate a refrigerator, highlighting a dual role of such devices.

In their recent experiments, Jaliel and her colleagues essentially built an energy harvester by placing two quantum dots beside a central cavity. They then controlled the energy levels of each dot by applying different voltages to their respective plunger gates and heated up the cavity by supporting ac currents in the nearby channel.



Credit: Dr. Reuben K. Puddy.

The harvester developed by Jaliel and her collaborators can, at least in principle, reach Carnot efficiency. In addition, it can be optimized to achieve a large power in combination with a high efficiency at maximum power.

"When the energy of electrons match the quantum dot energy, they can enter or leave the cavity through the dots," Gulzat Jaliel, one of the researchers who carried out the study, told Phys.org. "When the electrons enter into the hot cavity through lower energy level dot, and leave through the higher energy level one, they have to take some energy from the cavity to be able to complete the process, and therefore generate some thermal power from the hot cavity autonomously."

This experimental setup allowed the researchers to realize the new energy harvester. In real-world applications, however, the cavity used in their study could be warmed up using a variety of other sources, including waste heat from other quantum devices.

Interestingly, the energy harvester presented by Jaliel, Jordan and their colleagues could act as a green energy source when scaled up to millions or billions, as the waste energy it harvests would also increase in proportion. A further advantage of this quantum dot-based system is that it could be used to charge other devices in situations where there is a low supply of energy, such as satellites in places with large temperature gradients.

"The main purpose of our experiment was to demonstrate the theoretical proposal is realizable and reliable," Jaliel said. "Any further industrial applications will be very interesting to see too."

Other teams of researchers have built similar energy harvesters in the past. One example of this is a harvester realized by Holger Thierschmann et al., which was also based on the past study by Sánchez and Büttiker. Compared to this previously developed harvester, however, the device realized by Jaliel and her colleagues is easier to control, while also offering larger power and efficiency.

When collecting measurements at an estimated base temperature of 75 mK in a He^3/He^4 refrigerator, in fact, this new quantum dot energy harvester can generate a remarkable thermal power of 0.13 fW for a temperature difference across each dot of about 67 mK. In their future studies, the researchers plan to explore three possible strategies to further improve the harvester's performance. Firstly, they would like to redesign the dots to gain greater control of the tunneling rates, then scale up the device and improve its working temperature.

"Finer control of the dot tunneling rates should allow near ideal Carnot efficiency to be realized," Jaliel said. "Scaling up the power could be achieved with resonant tunneling quantum wells, as also predicted by the theoretical part of another study by Björn Sothmann, Rafael Sánchez, Andrew N Jordan and Markus Büttiker. I did attempt to experimentally realize this device during my Ph.D. study, but unfortunately I ran out of time before finishing it. I would really like to give it another go if I have the chance."

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